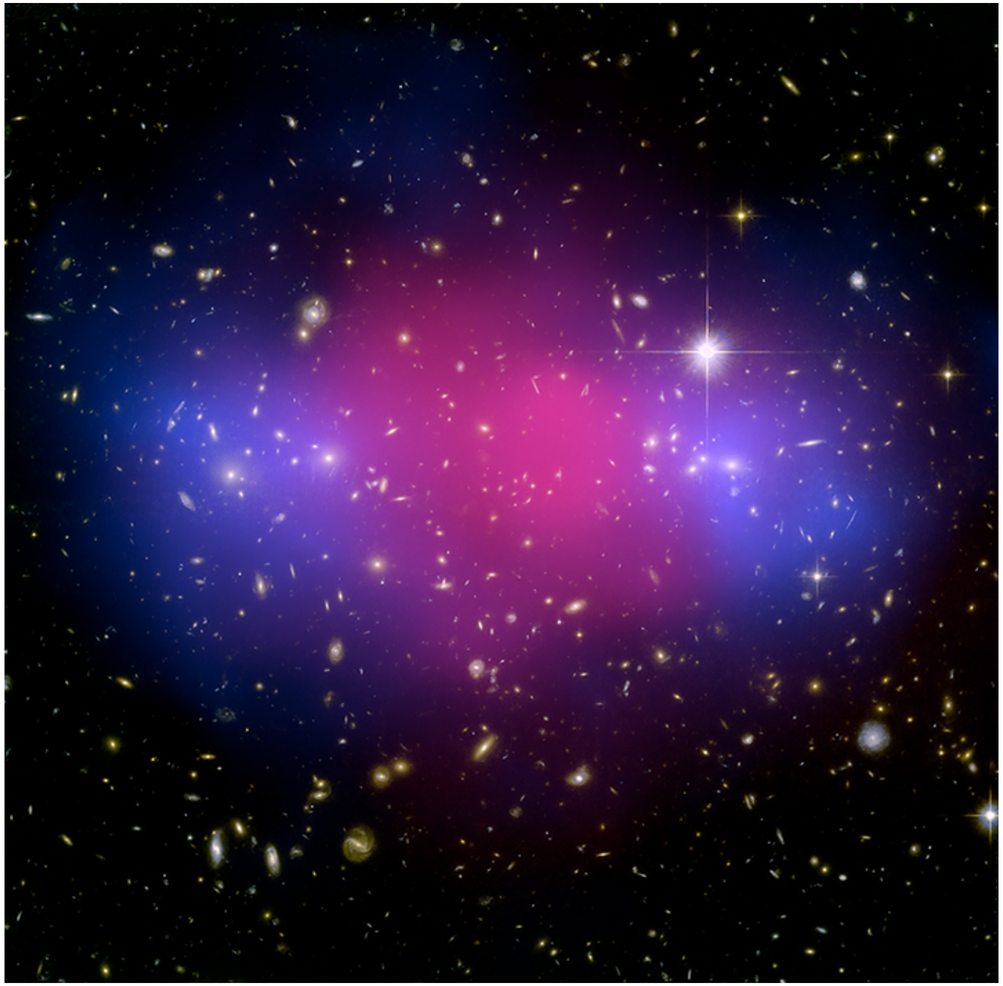


Clusters are most massive virialized systems.
Mostly dark matter
~85% of baryonic matter is hot gas

Cluster Physics

Jones, Arnaud, Markevitch, Forman, Sun, David, Bohringer, Molendi, Vikhlinin, Giantucci, Pratt, Croston, Million, et al.

Outline

Cluster and group properties, including gas at large radii and heavy element enrichment of the ICM

Growth of clusters through mergers

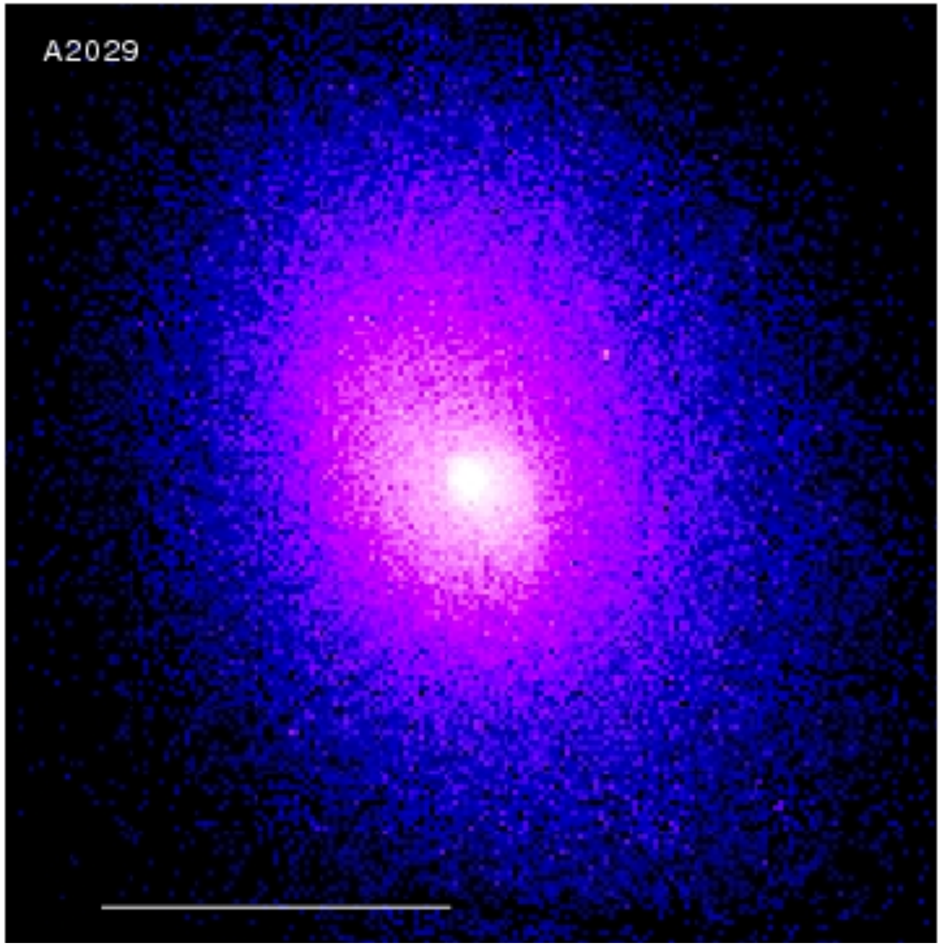
Major mergers, radio halos, a twisted radio source and near misses

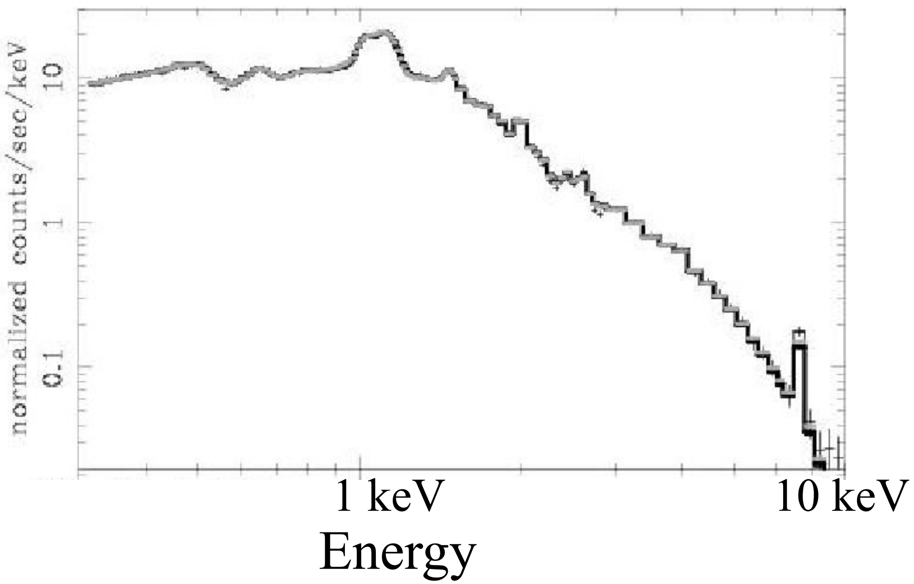
Need for multiwavelength observations, simulations/theory and future X-ray missions!

X-ray Directly Measured Cluster Properties

X-ray flux & cluster morphology X-ray spectra

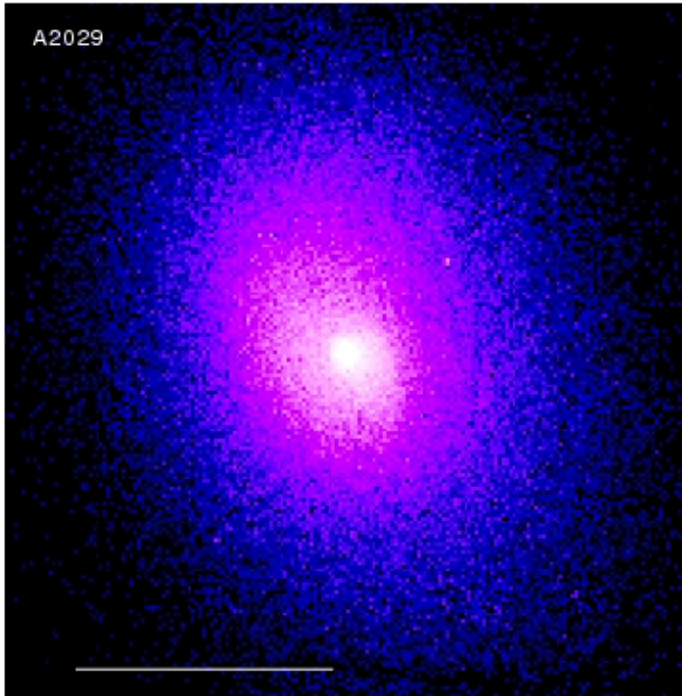
Luminosity, redshift, gas temperature, density, gas mass, pressure, entropy, metallicity, total cluster mass



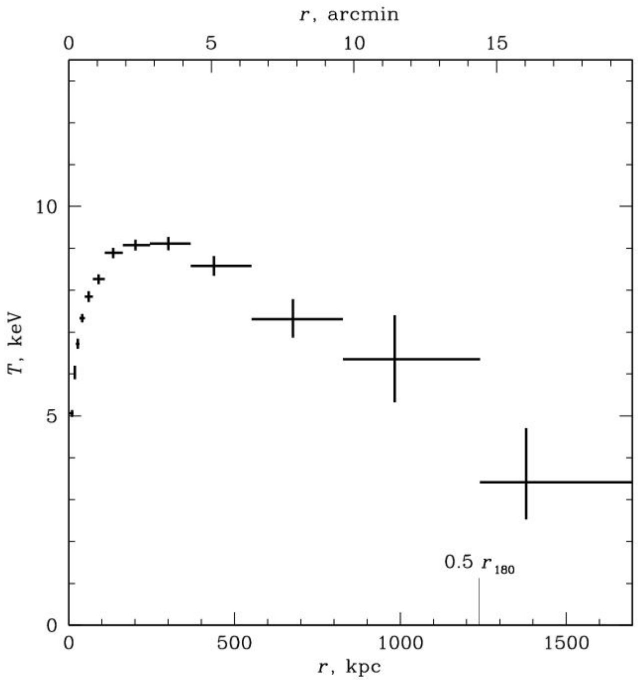


X-ray Measured Cluster Properties

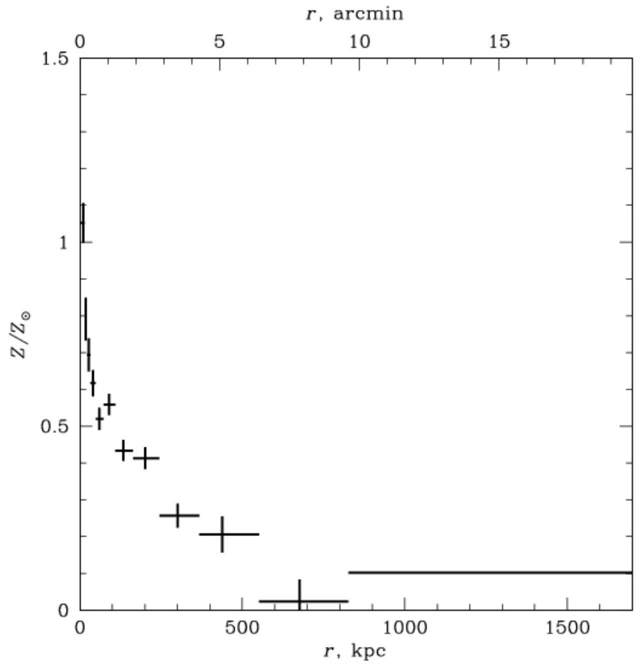
X-ray spectra + redshift (can come from spectrum) + atomic physics . => temperature and abundance (metallicity) profiles



A2029 X-ray image

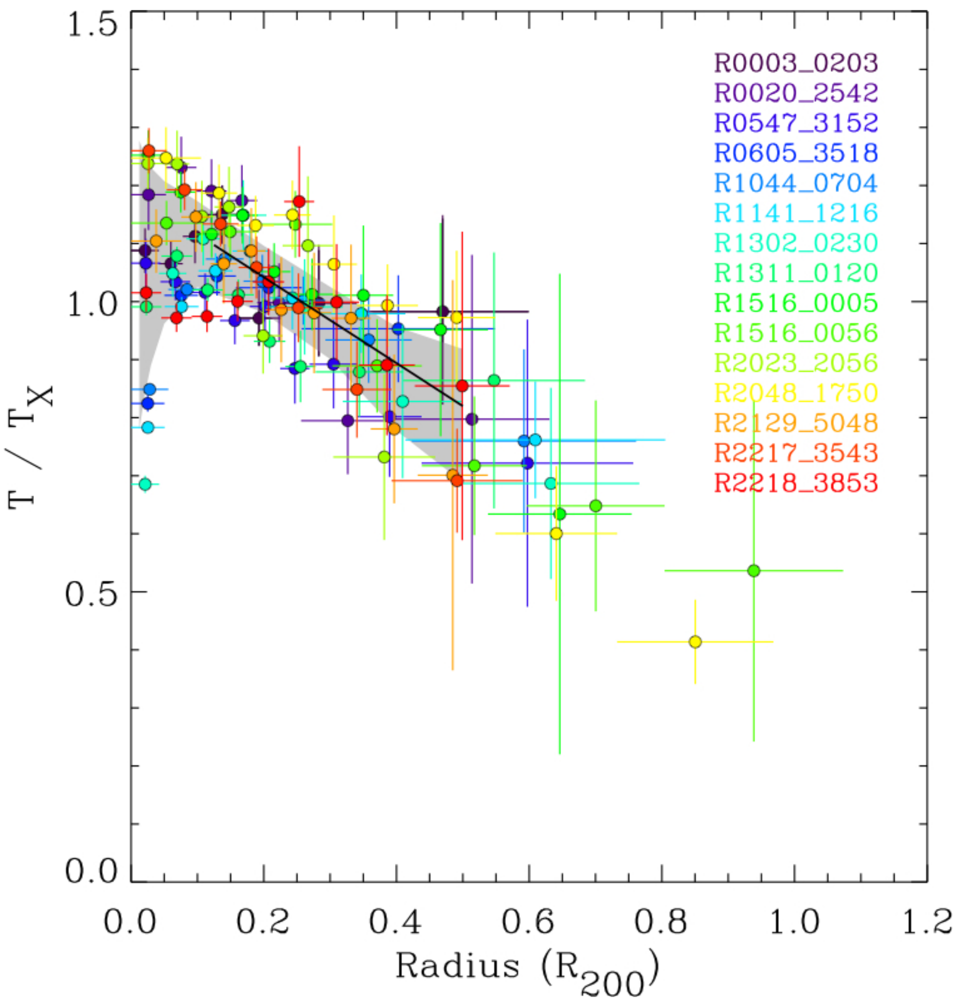


Temperature profile - cool core

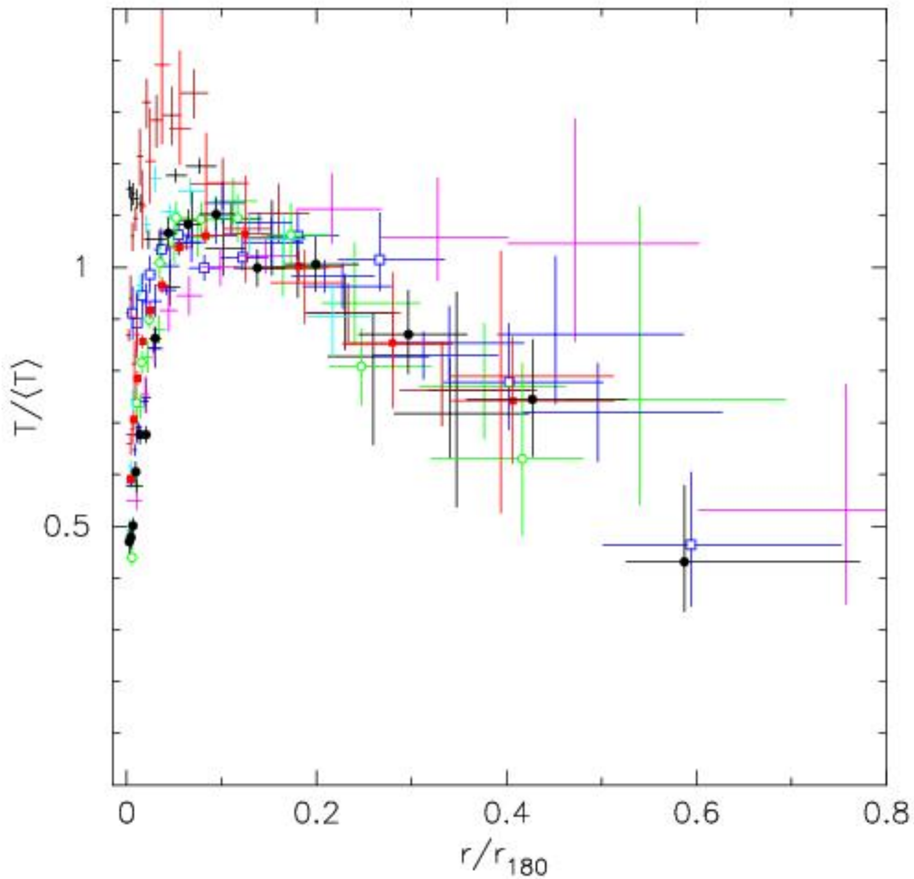


Centrally peaked metallicity

Cluster temperature profiles - "universal" profile in undisturbed systems

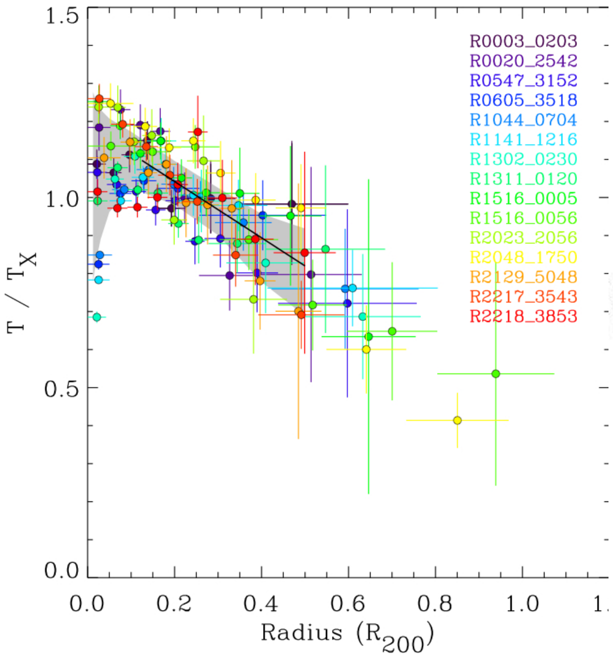


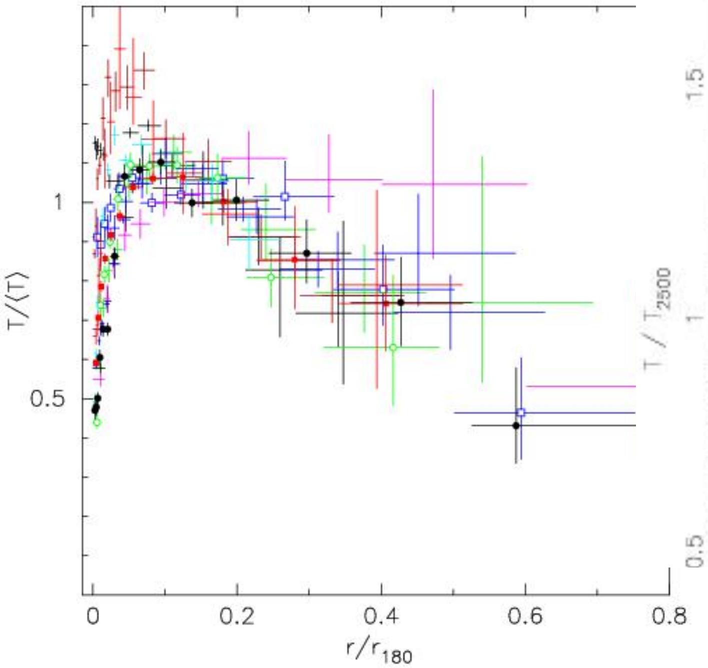
Pratt et al. (XMM_Newton)

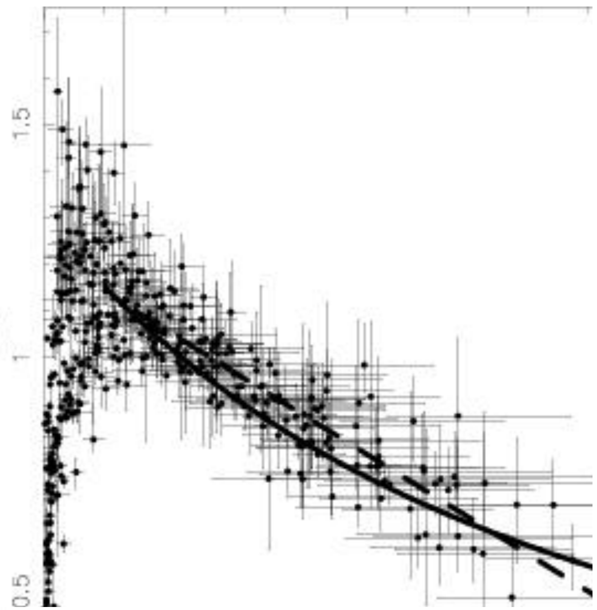


Vikhlinin et al. (Chandra)

Cluster temperature profiles - “universal” profile in undisturbed systems - including groups?



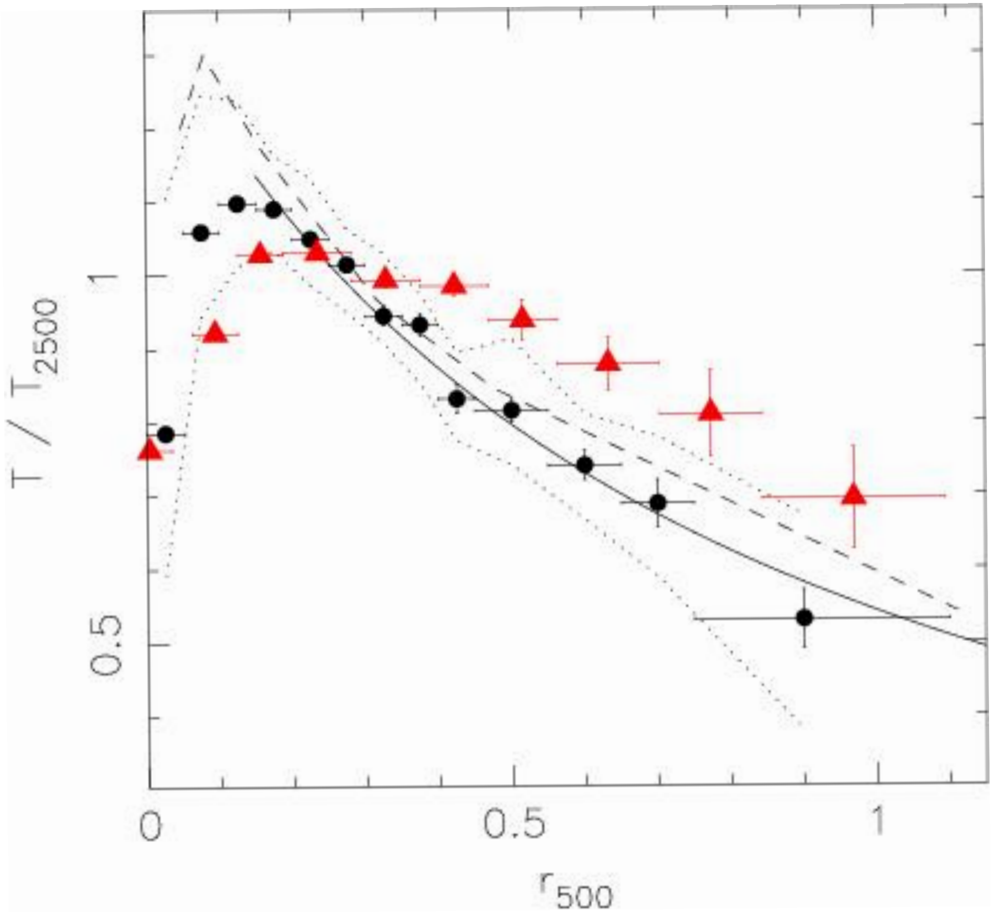




Pratt et al. (XMM_Newton) Vikhlinin et al. (Chandra)

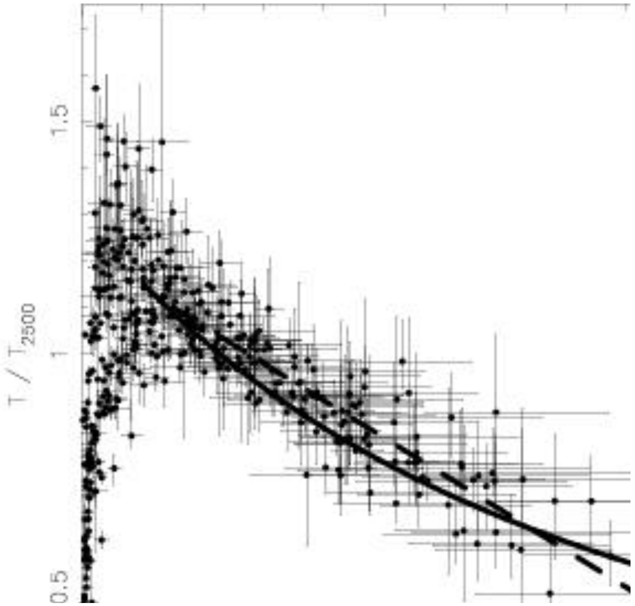
Groups - Sun+2009

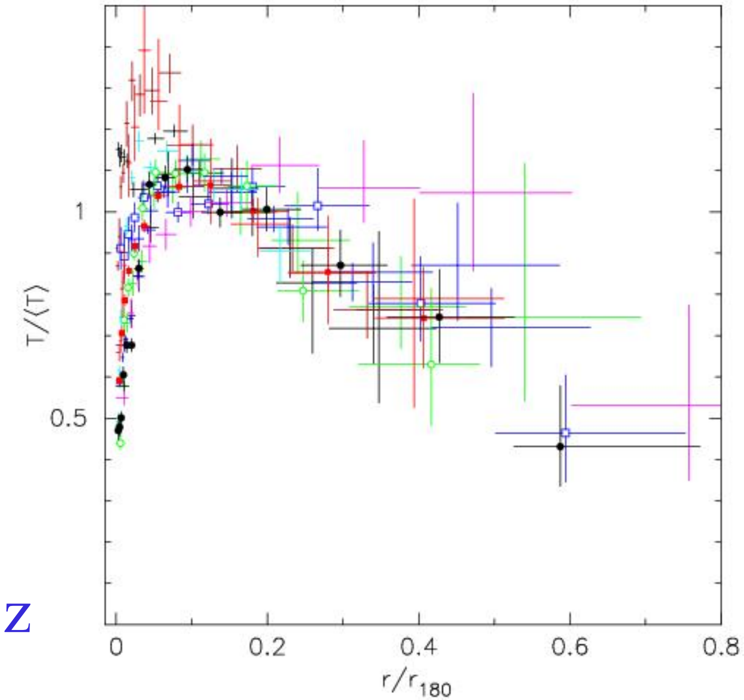
Temperature profiles - differences between clusters and groups



Groups (black) - clusters (red)

Sun et al.

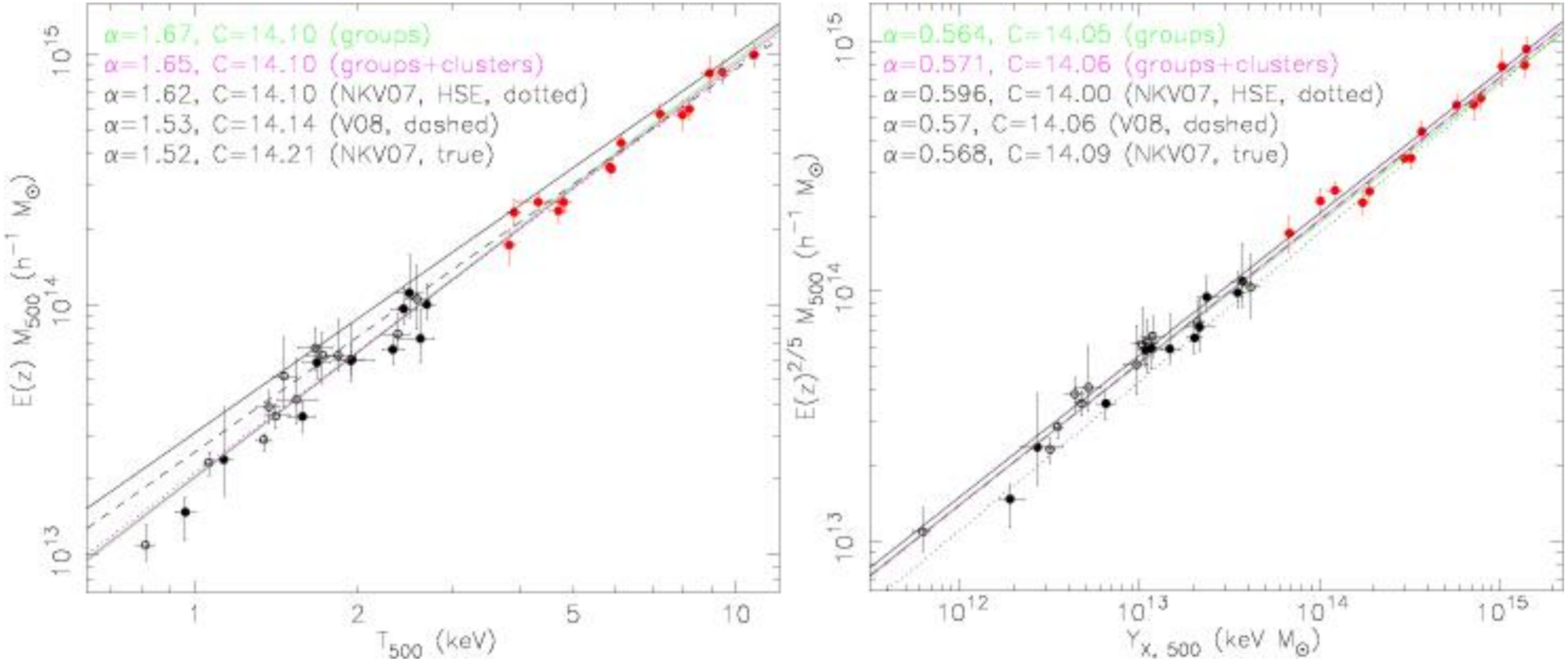




IXO will measure with z

Cluster and group masses

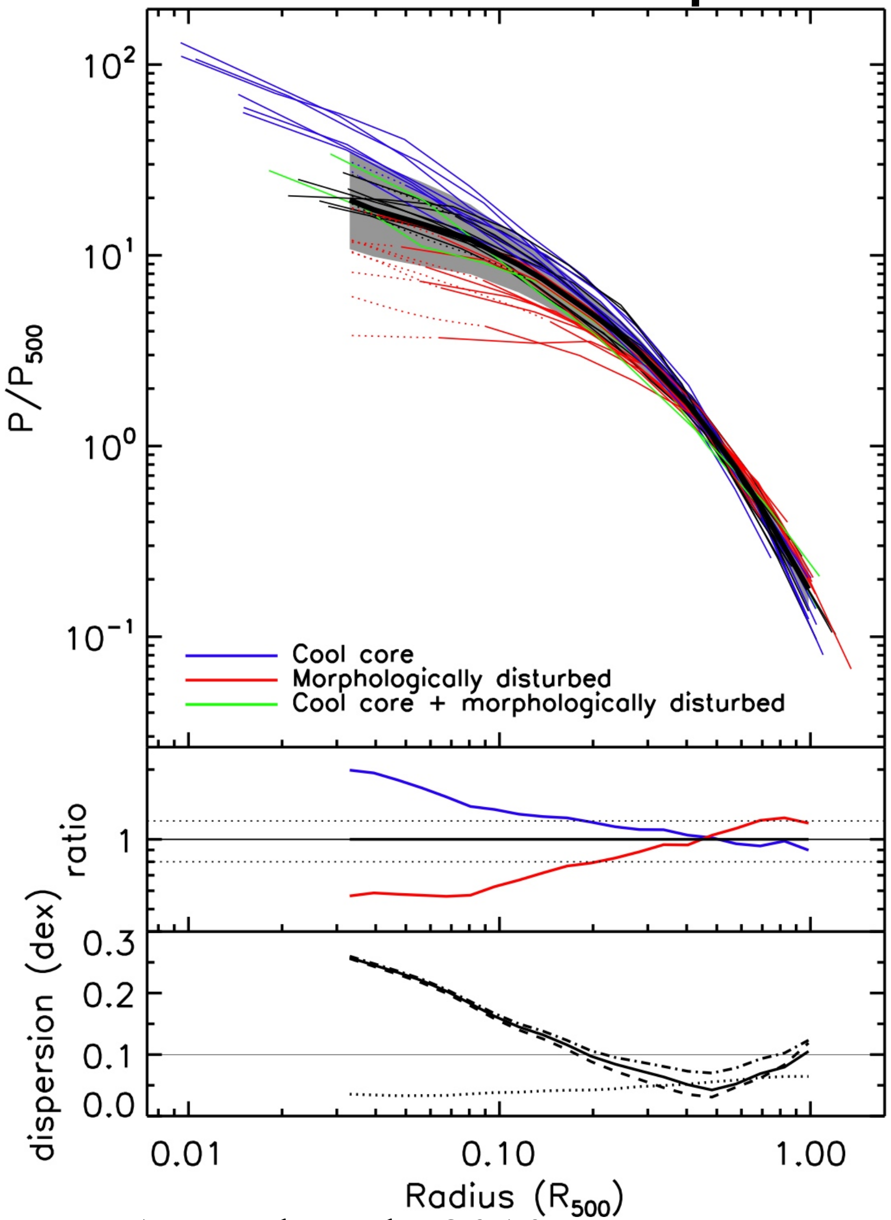
If gas is in hydrostatic equilibrium, total mass determined from density and temperature profiles. Or use mass proxies (e.g. gas mass, Yx)



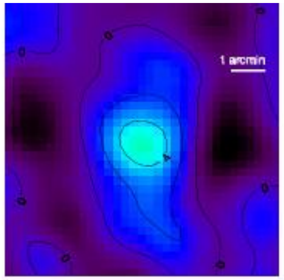
Difference between HSE prediction and groups may suggest that gas turbulence more important in groups - IXO will measure this

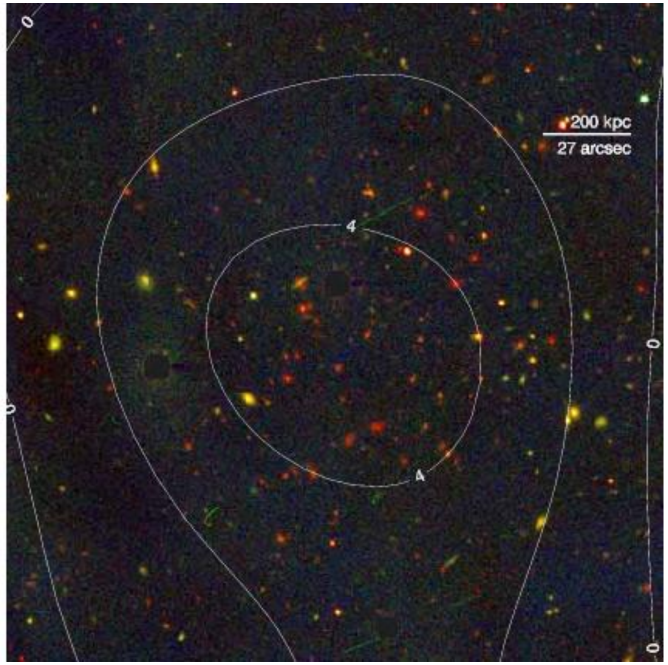
Sun et al. 2009

Profiles of cluster pressure from X-rays and SZ



Arnaud et al. 2010

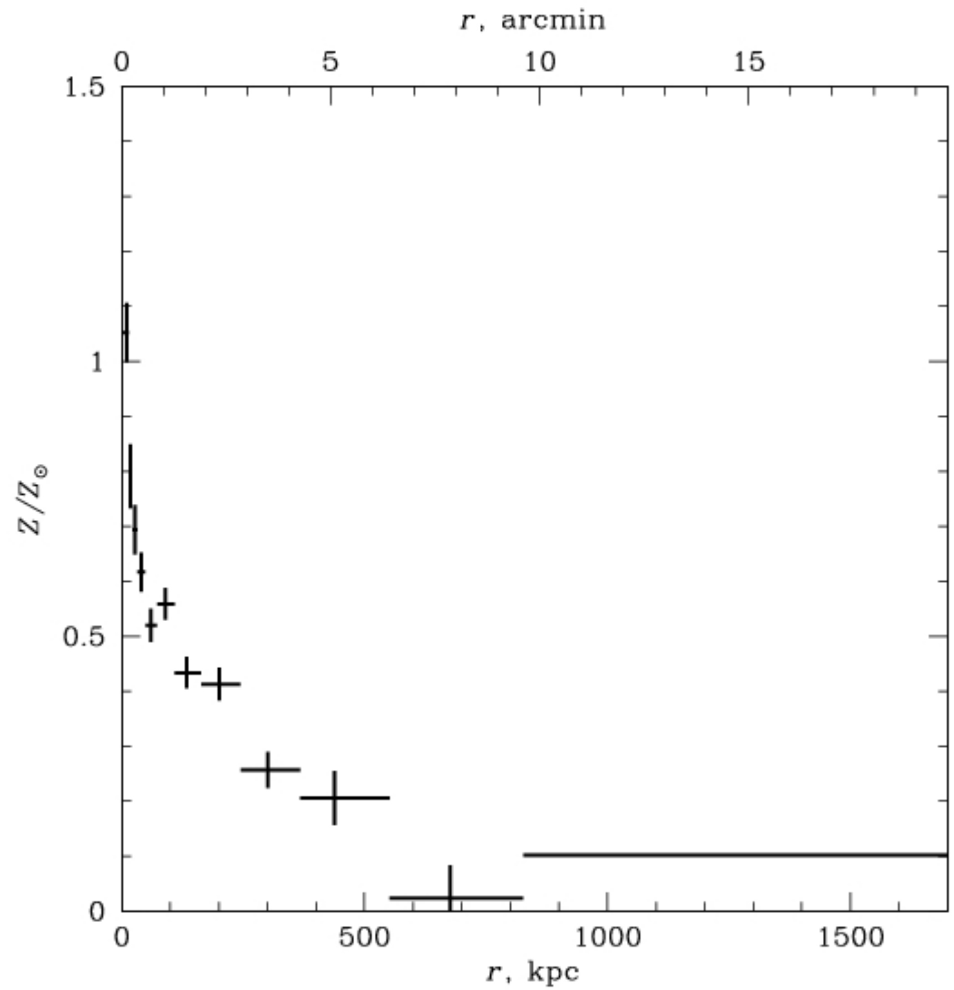


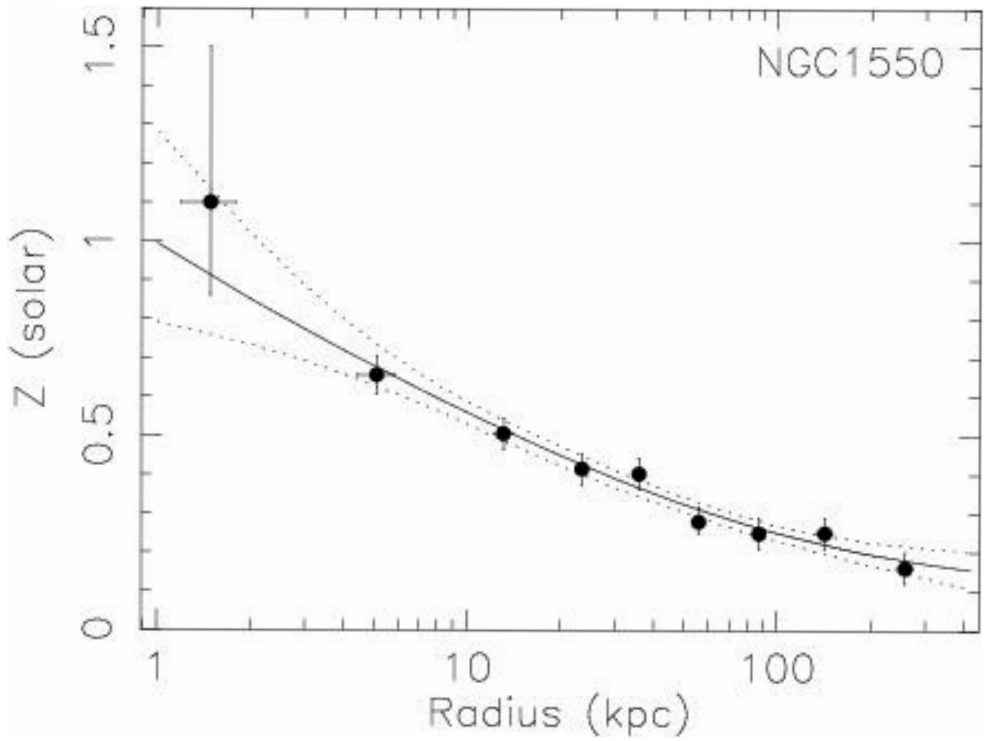


SPT SZ discovered cluster

High et al. 2010

Abundance profiles for clusters and groups centrally peaked on bright galaxy

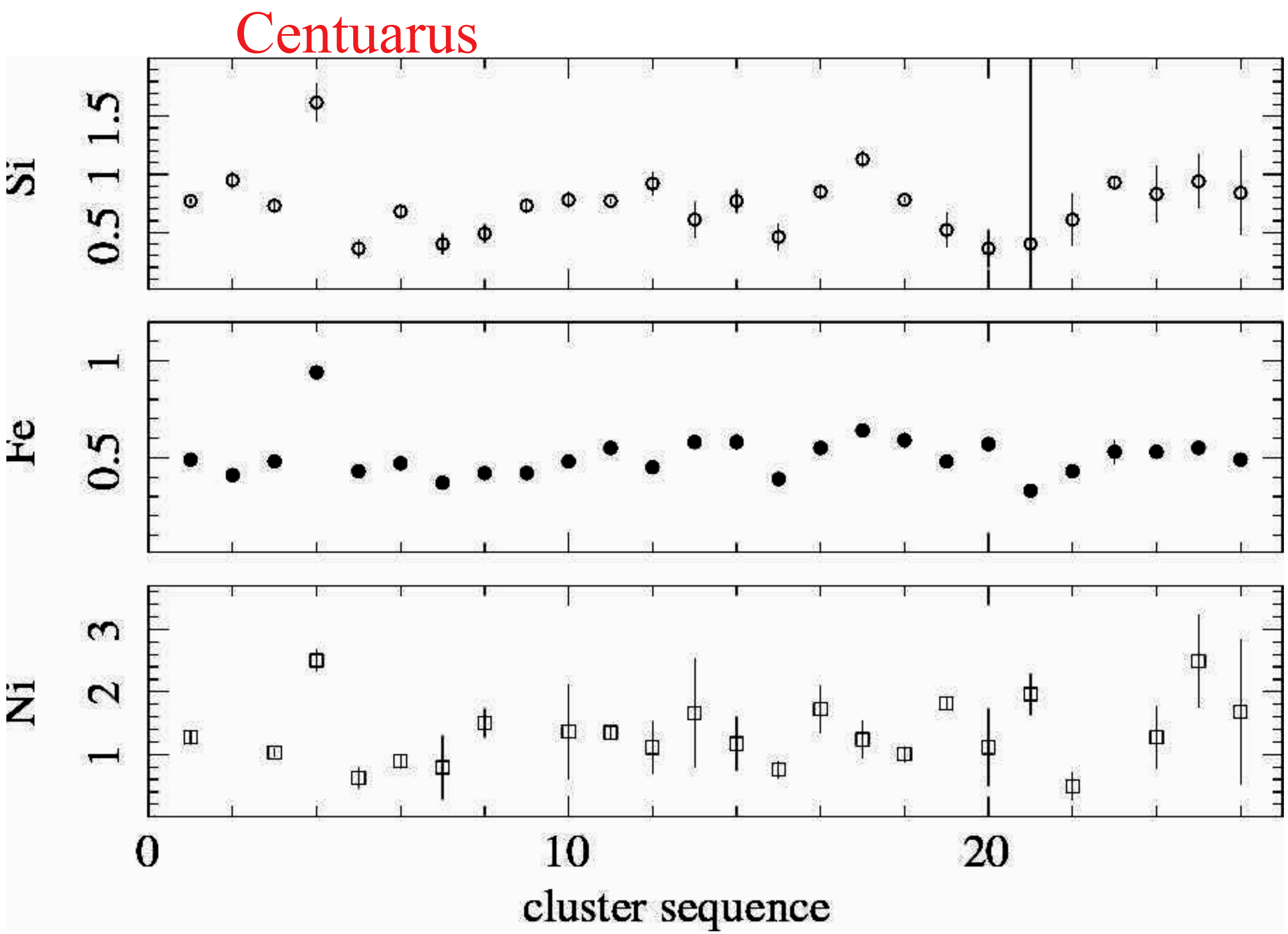




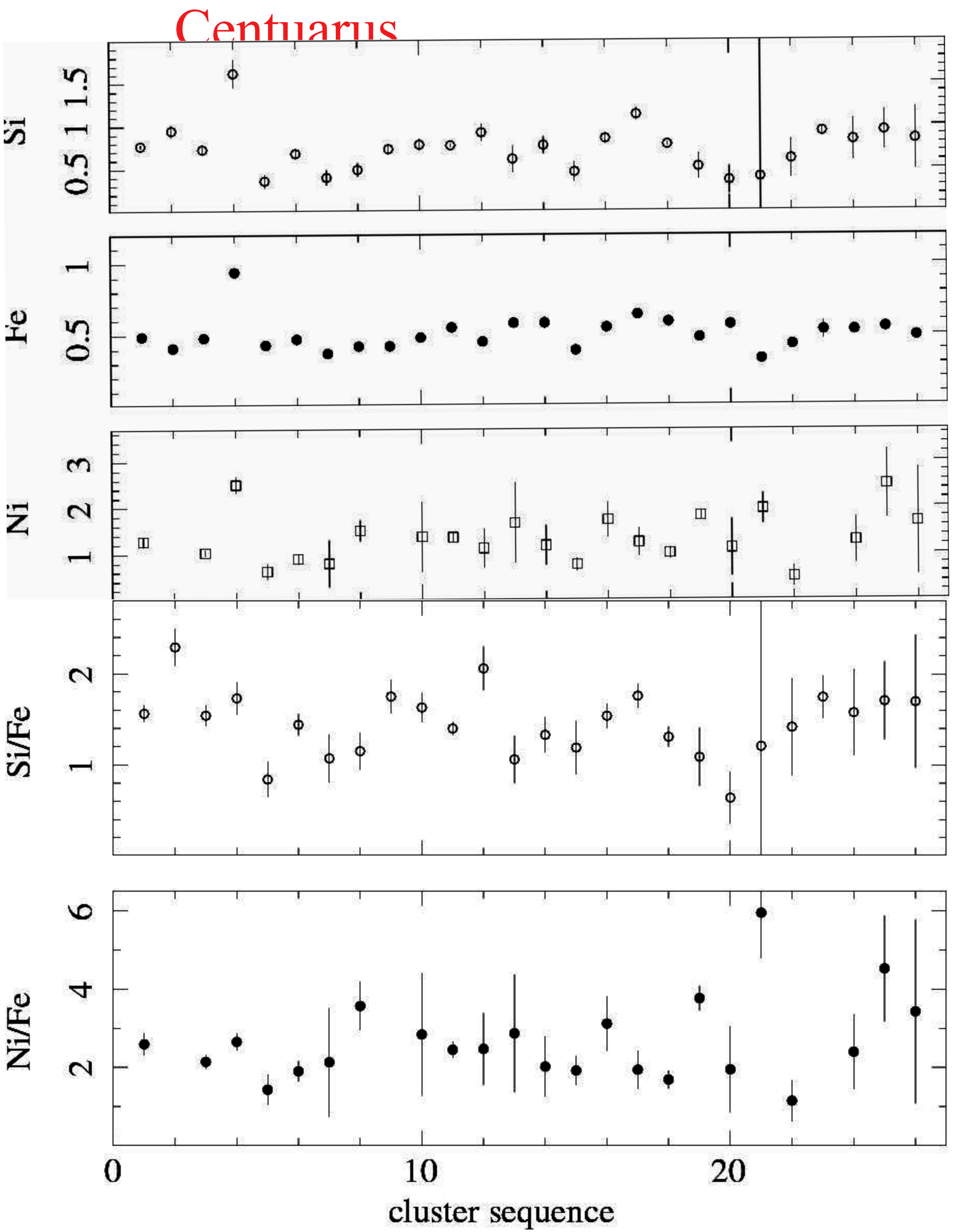
A2029 cluster (Vikhlinin et al.)

NGC1550 group (Sun et al.)

Abundances in the cores of cool-core clusters



De Grandi & Molendi (2009) IXO will **map** abundances in cluster gas



Abundances in the cores of cool-core clusters

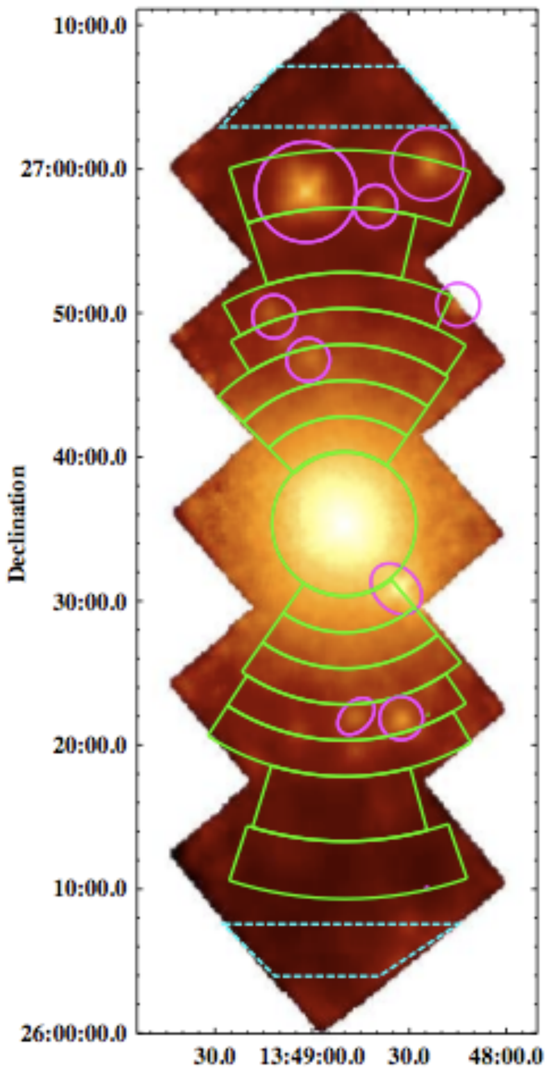
De Grandi & Molendi 2009)

Si/Fe

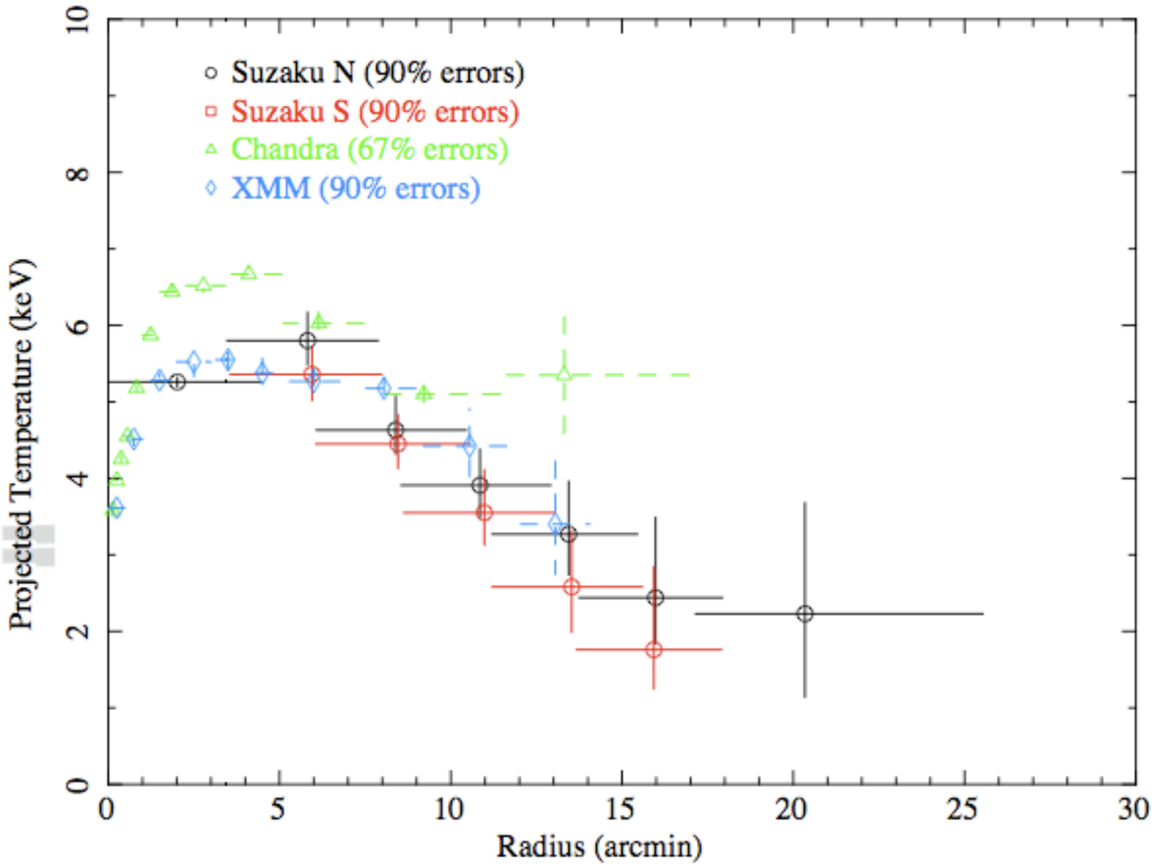
Ni/Fe

IXO will map abundances

Cluster Physics - mass measurements at large radii - r_{200}

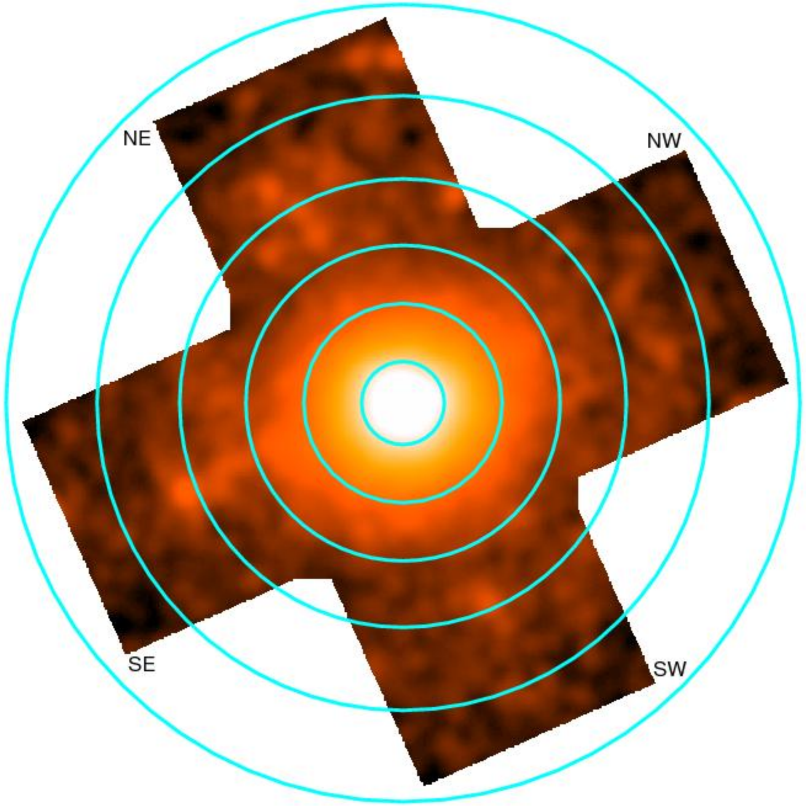


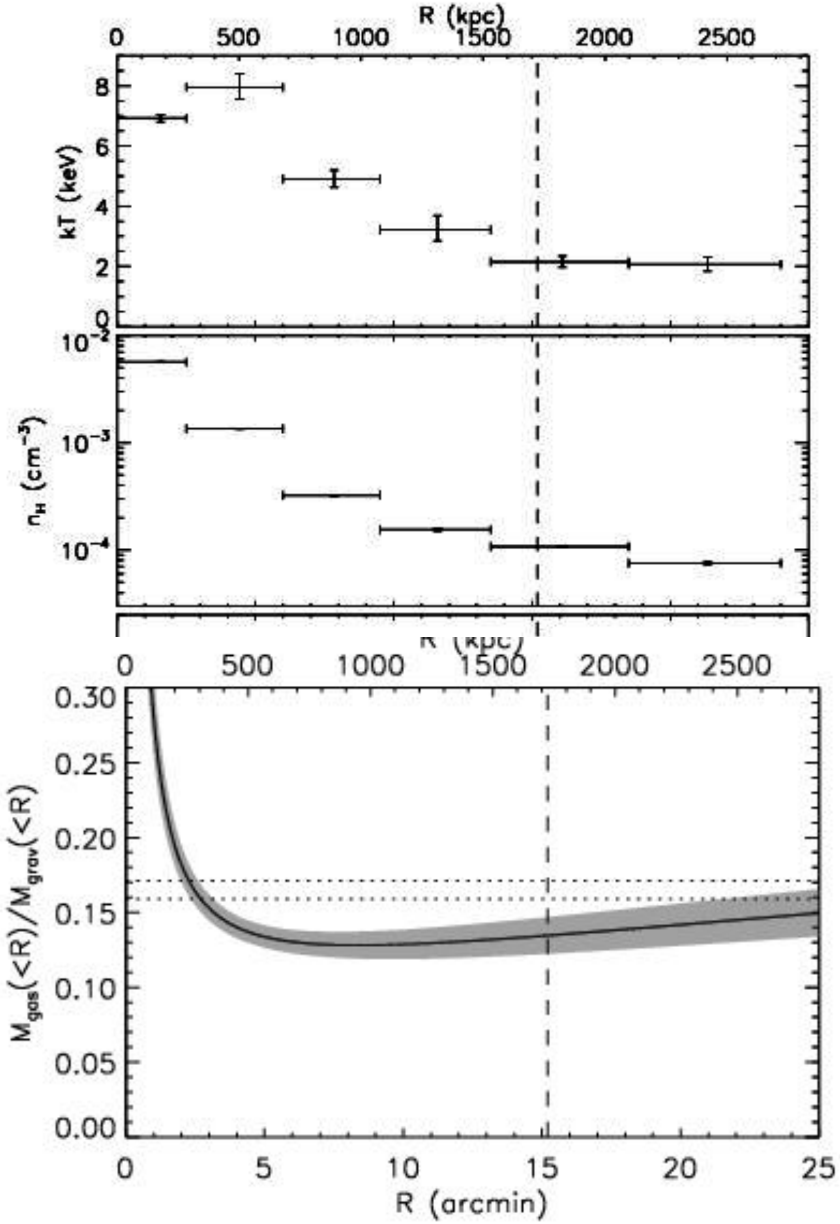
Suzaku X-ray observations A1795
(Bautz et al. 2009)



Low background is important

Cluster Physics - mass measurements at large radii - r_{200}

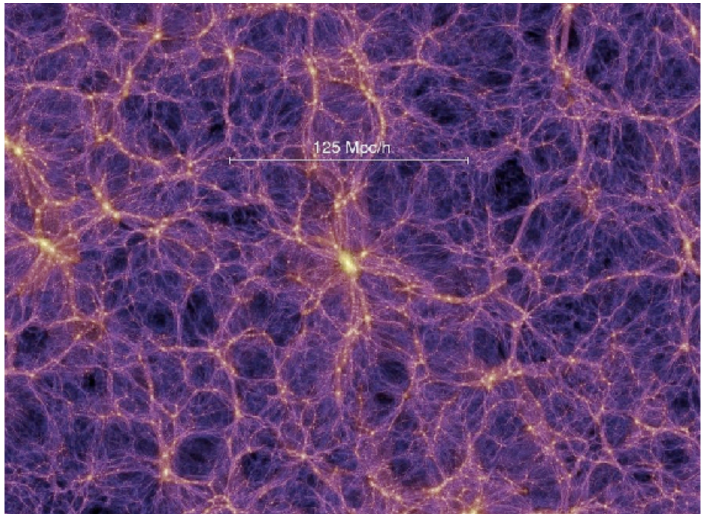




Suzaku observations
PKS0745-191
(George et al 2009)

Low background is important

Cluster growth through mergers

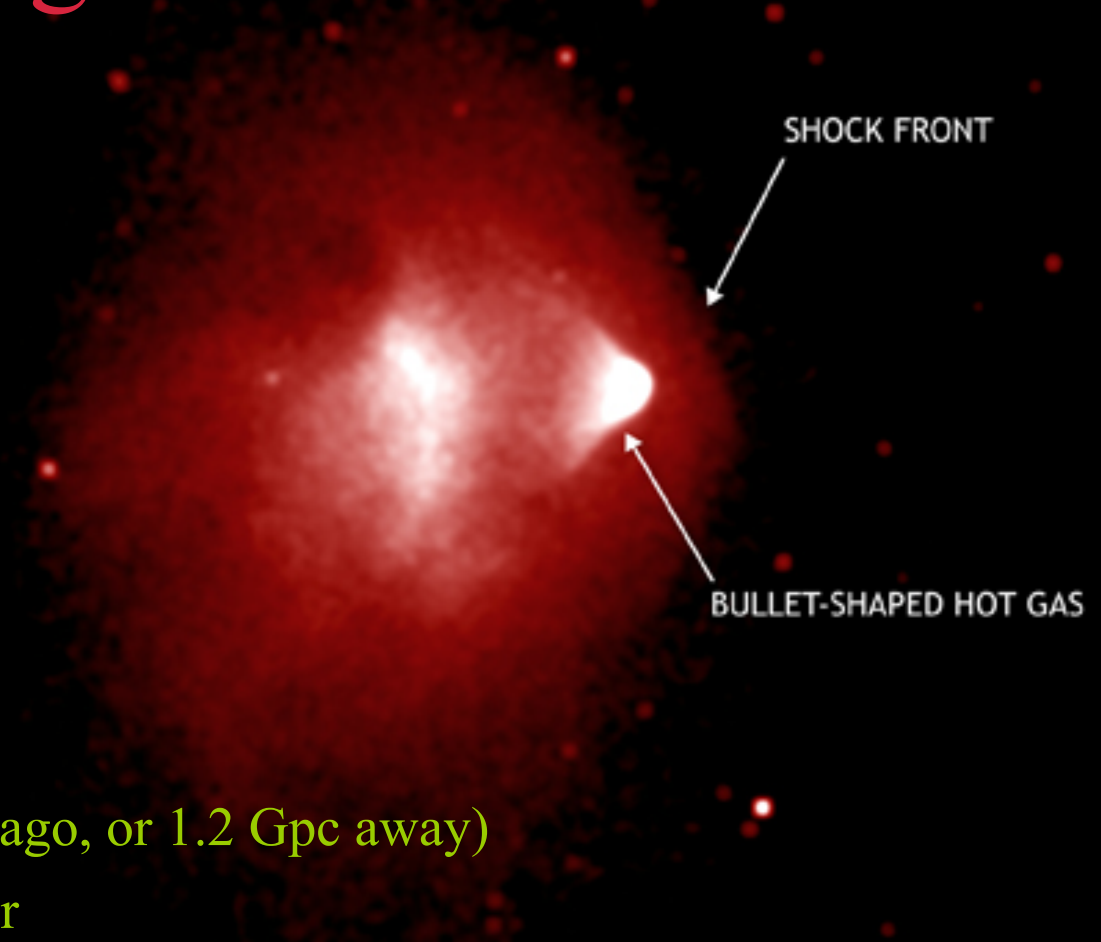


Millenium simulation

Bullet cluster

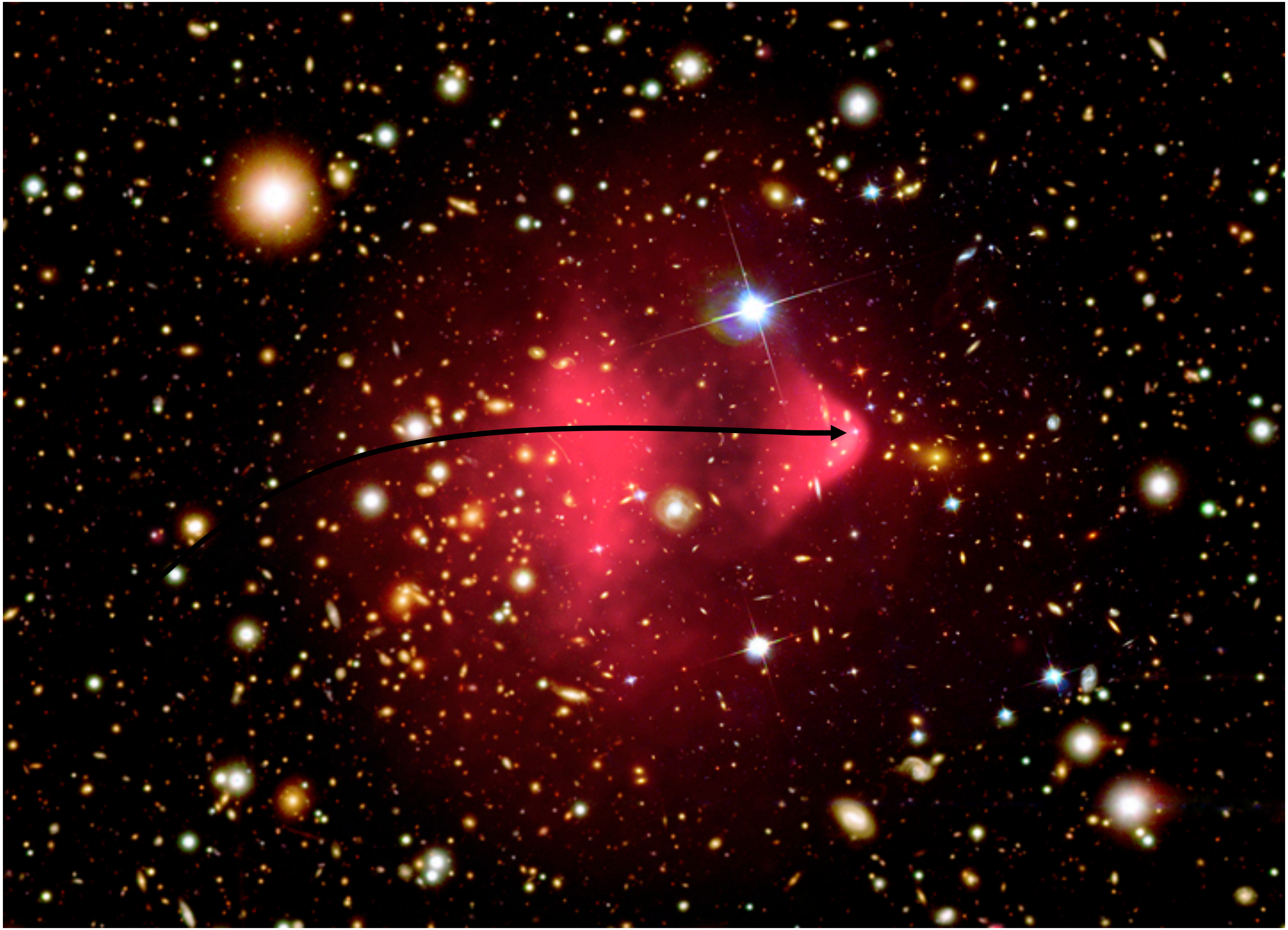
Cluster mergers - extremely energetic~ 10^{64} ergs

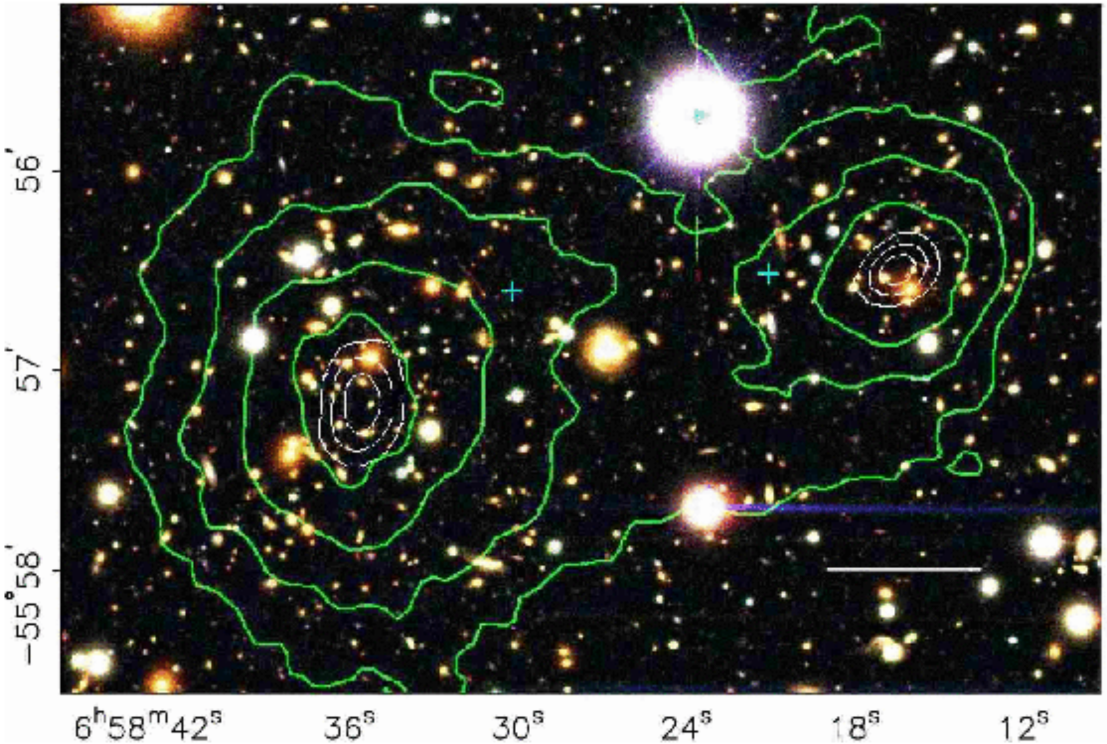
1E0657-56 (The Bullet Cluster)
Making the hot ICM hotter



- Vital Statistics
  - z=0.30 (3.35 Gyr ago, or 1.2 Gpc away)
  - Supersonic merger
  - In plane of sky (+/-15 degrees)
  - Speed ~ Mach 3 (4500 km/s)
  - T_{bullet} ~ 6-7 keV

Markevitch et al.
Clowe et al.





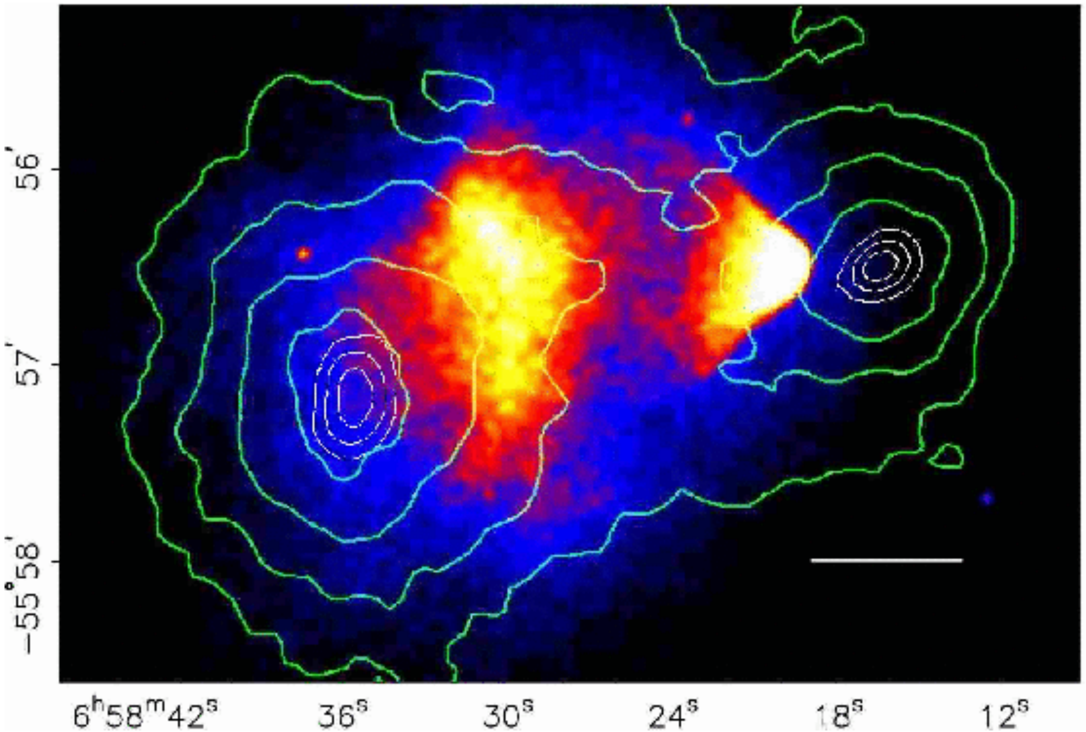
Dark matter vs Luminous matter

Clowe et al. (2006)

Bradac et al. (2006)

Data: 500 ks Chandra

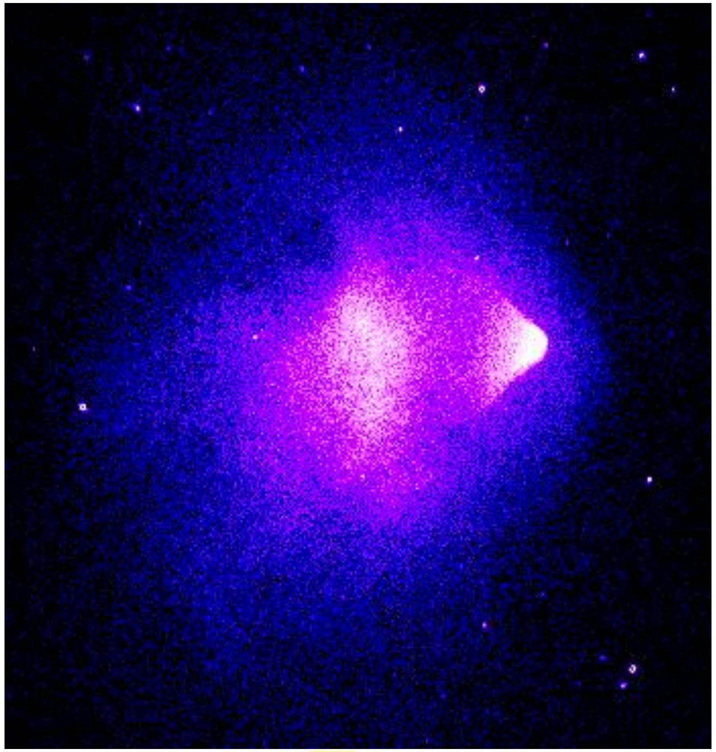
Magellan + ESO + HST imaging

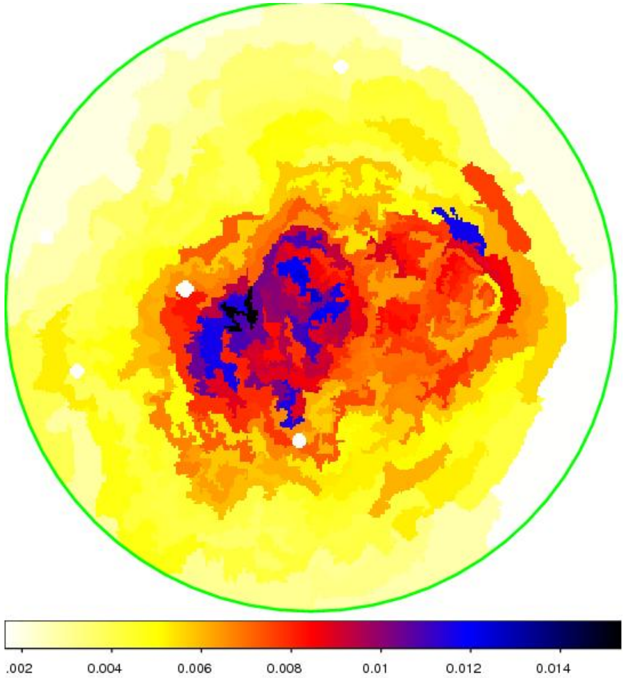


Results:

Offsets between gas and DM peaks for both main and subcluster

No offset between galaxies and DM





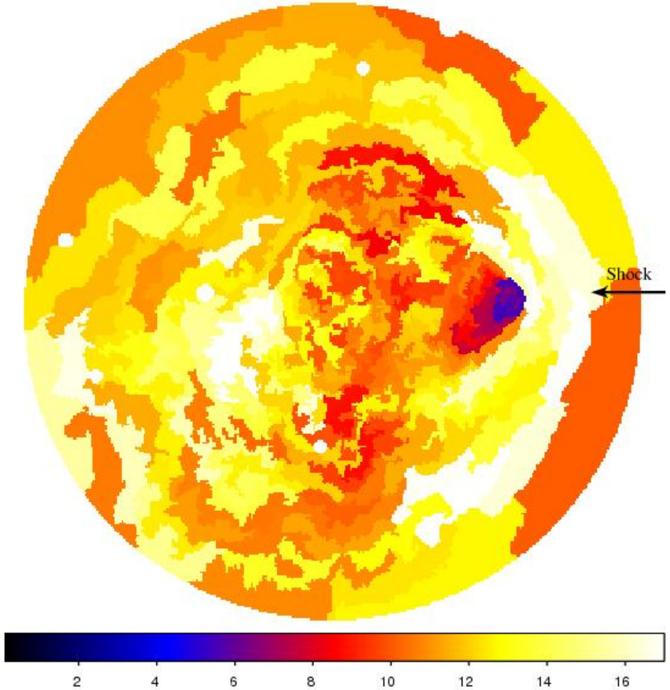
Gas pressure

Million + 2010

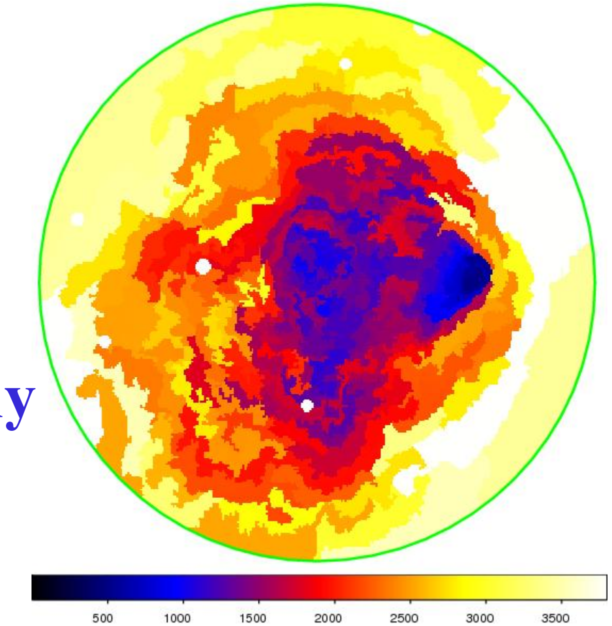
Bullet

500 ks

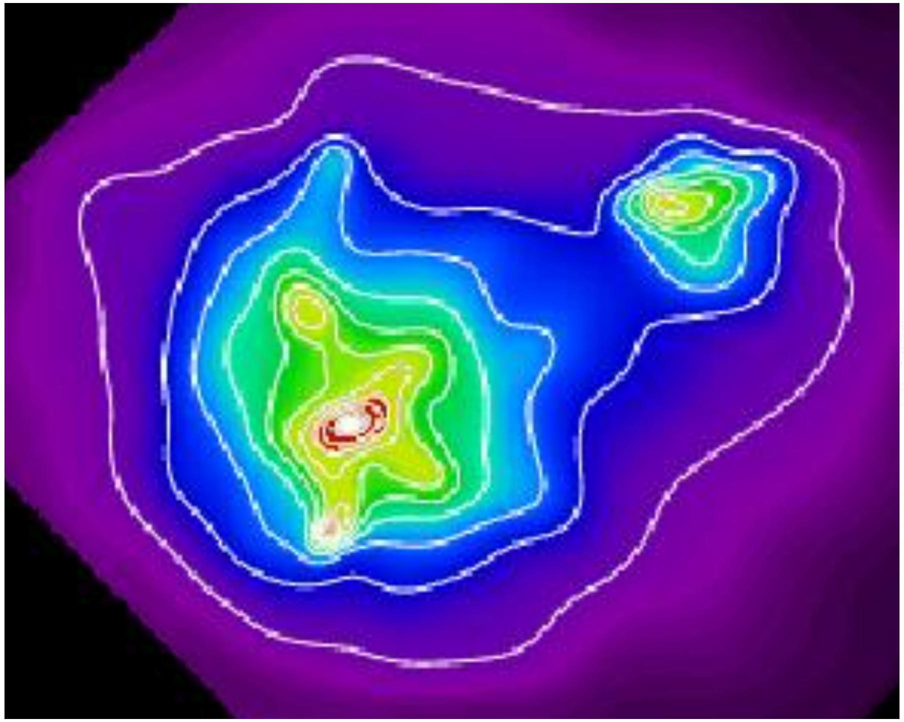
IXO can study many more

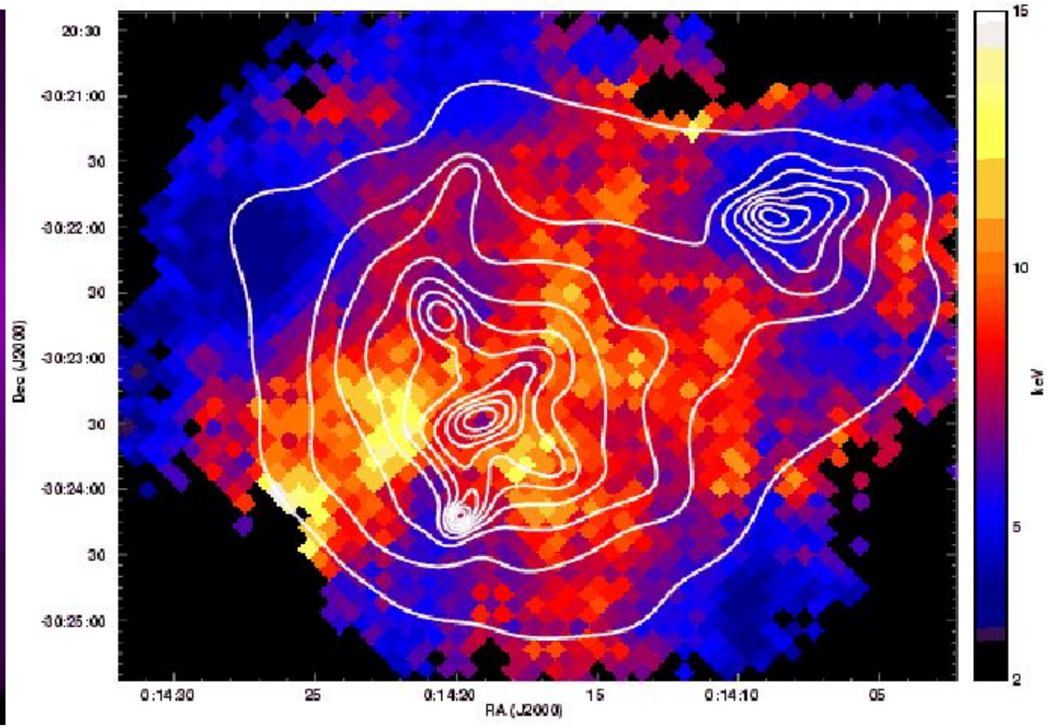


Gas temperature



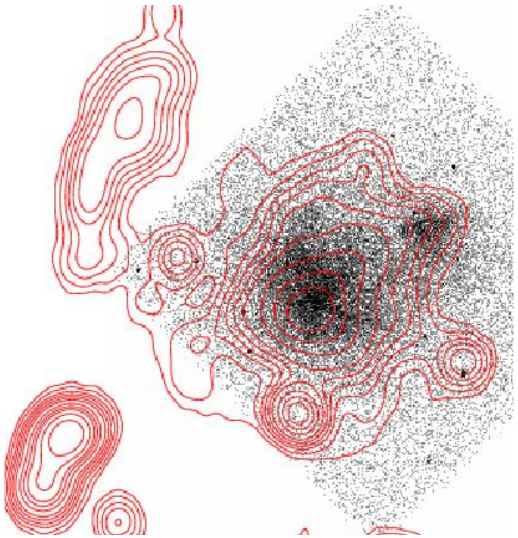
Gas entropy





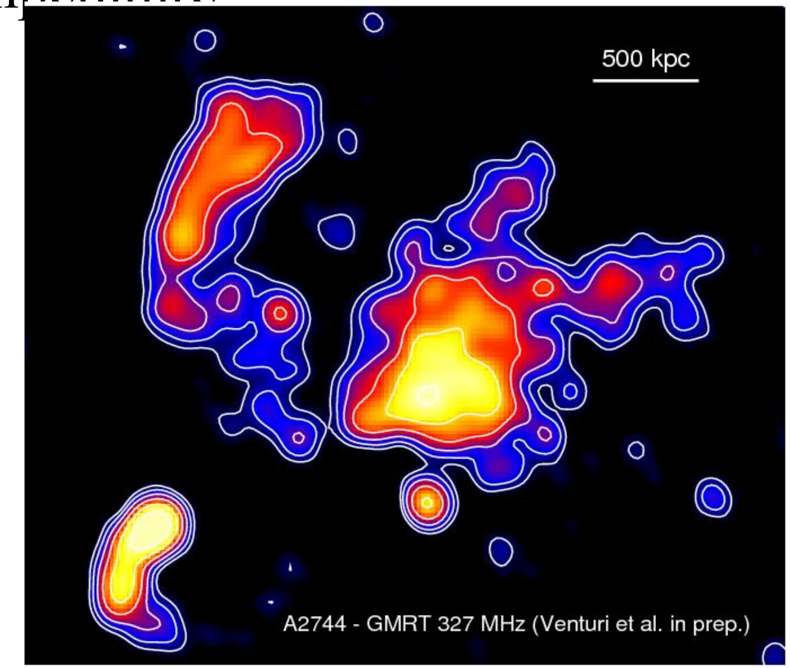
A2744 temperature

Kempner & David (2007)



Radio contours

A2744
merger



Giant Radio Halos
(more with LOFAR)

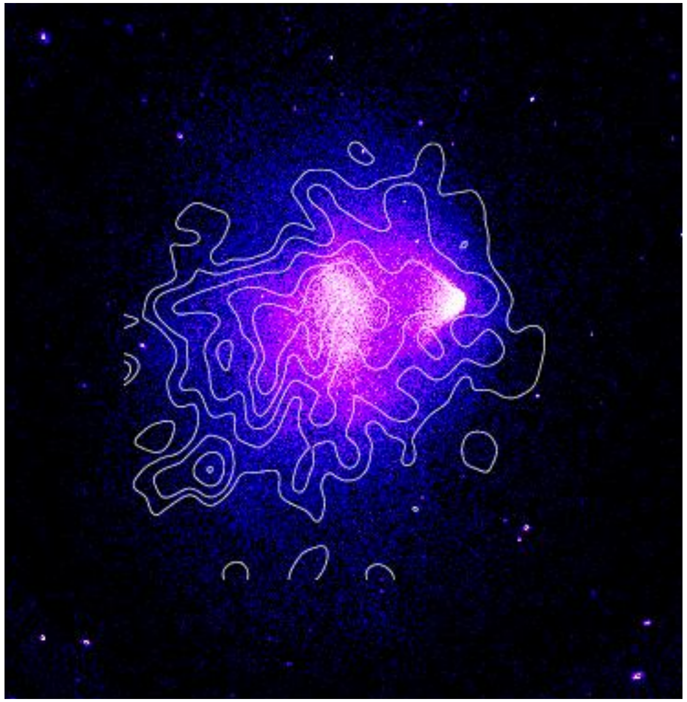
In merging clusters

Electrons (re)accelerated by gas turbulence due to merger

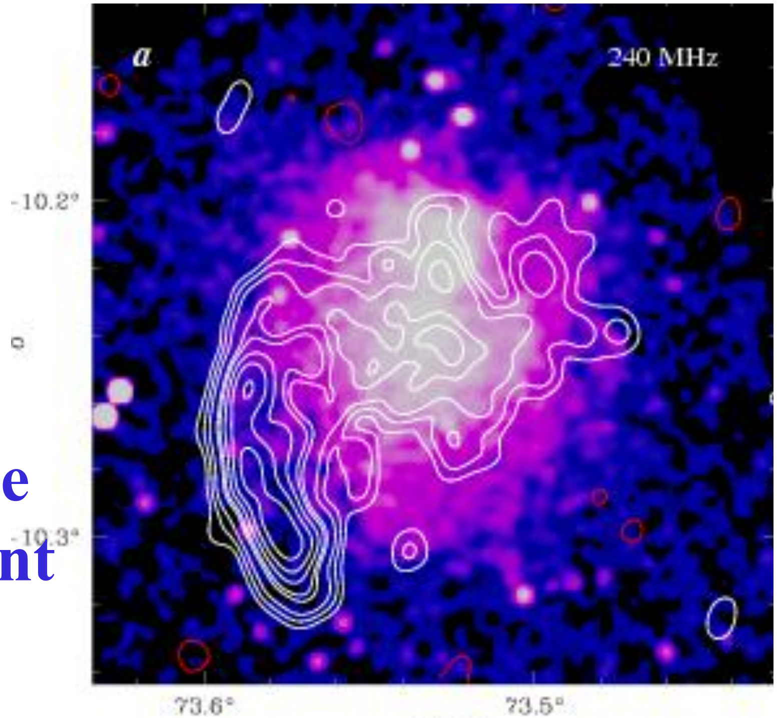
Hard x-ray component (IC, synchrotron, shocks??)

X-ray + radio to constrain magnetic fields

XMS will measure turbulence
HXI will map hard component



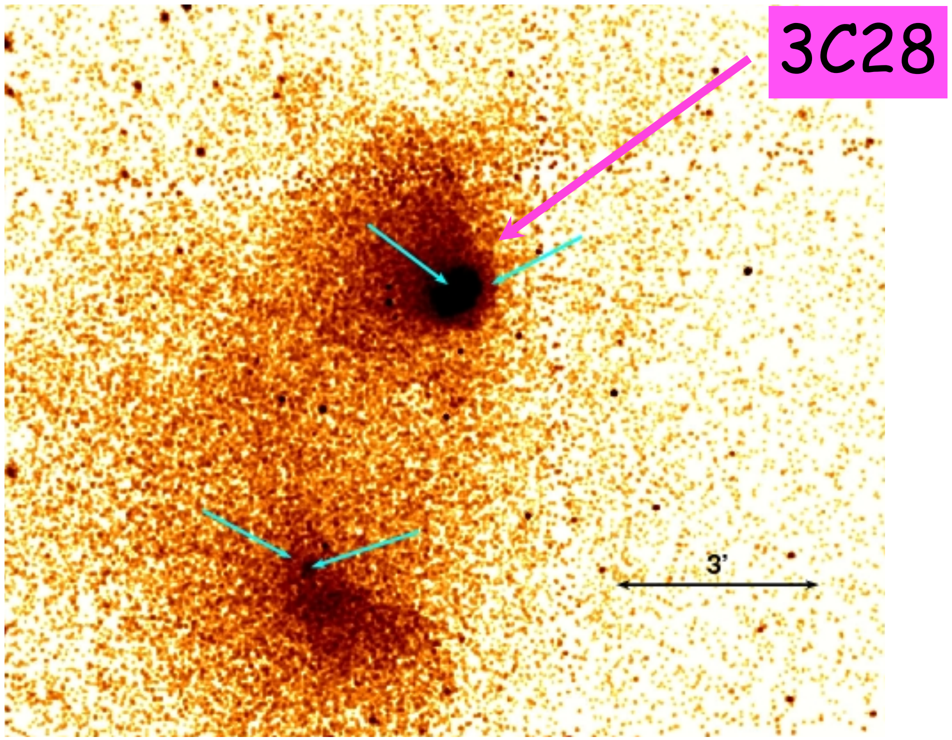
The Bullet



A520

A115 - another cluster merger

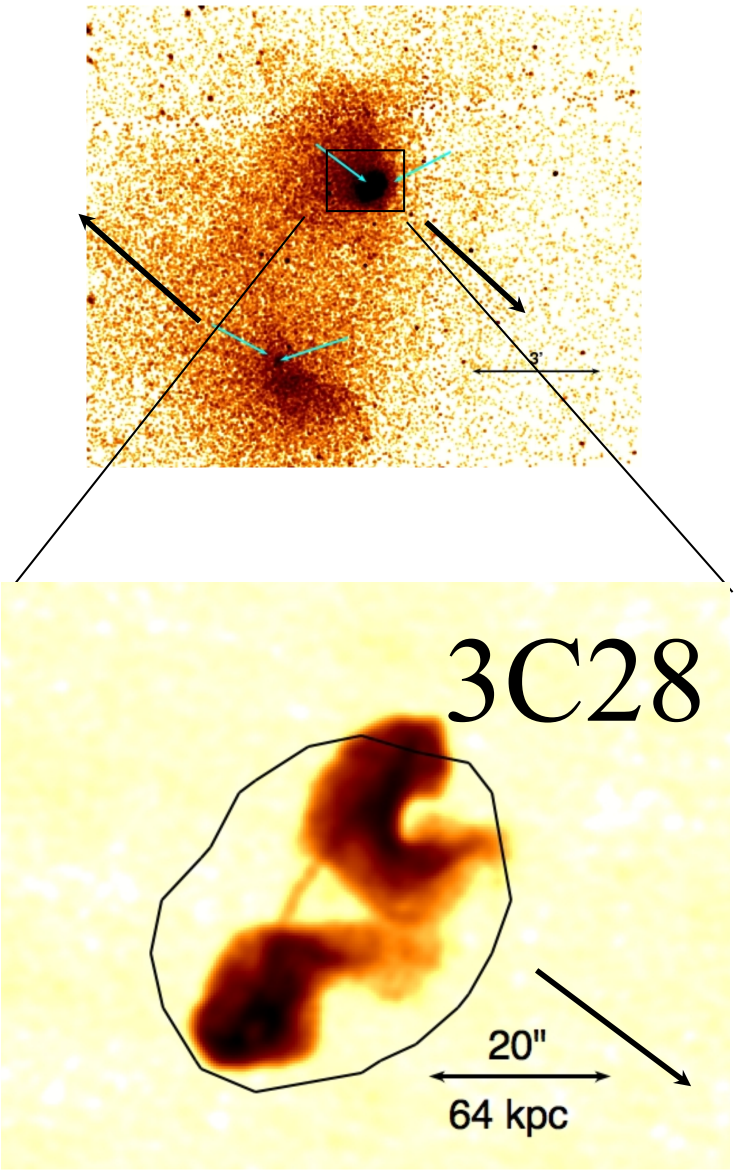
- 900 kpc separation (z=0.1961)
- 1 Mpc radio relic(Govoni+2001
- Subcluster components
  - bright cores (2-3 keV)
  - 2-3 x 10^{44} erg/s
  - thin surrounding shells
  - Embedded in surrounding cluster gas (7-8 keV; c_s~1400 km/s)
  - hot intermediate region (Chandra and ASCA - kT>10 keV)



Non-radial merger
L-O-S velocity difference ~1300 km/s
$v_{merger} \sim c_s$ (depending on projection)

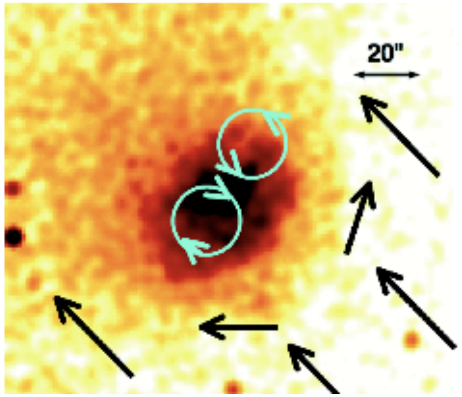
Gutierrez & Kruzienski (2005)
Forman et al. (2010)

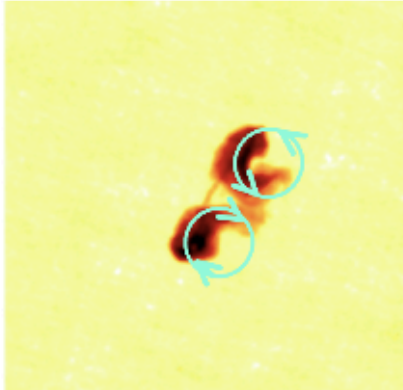
- Filamentary radio lobes with tails
  - Buoyancy (since central galaxy argues against large motions) Feretti +84
  - Ram pressure from motion to the NE Giovannini+87
- But
  - X-ray shows motion to SW with ram pressure stripped tail
  - Core gas not seeing direct ram pressure (yet)
- How can we explain the radio pointing IN the direction of motion?



Measure flow velocities

A - measure flow velocity
B - compute internal velocity
(assuming ideal potential flow)





A1) Using standard cold front analysis model edge to derive p_{edge} & $p_{free\ stream}$ gives velocity (Vikhlinin+01 as for A3667)
A2) In context of ideal potential flow, measure pressure around the body using non-parametric deprojections (as in Churazov+08)

$$v_{flow}^2 = 2\frac{\gamma}{(\gamma-1)}\frac{kT_b}{\mu m_p}\left\{1-(P_s/P_b)^{(\gamma-1)/\gamma}\right\}$$

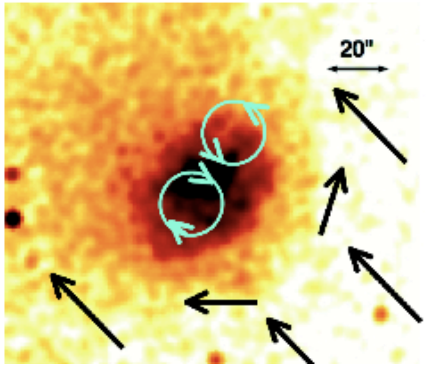
B With v_{flow} and density in/out, compute v_{rot}

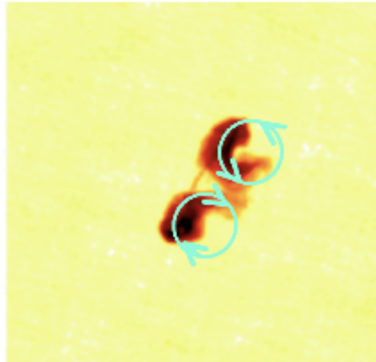
$$\rho_{out} v_{flow}^2 = \rho_{in} v_{rot}^2$$

Systematic errors from uncertain geometry

Future Prospects for A115

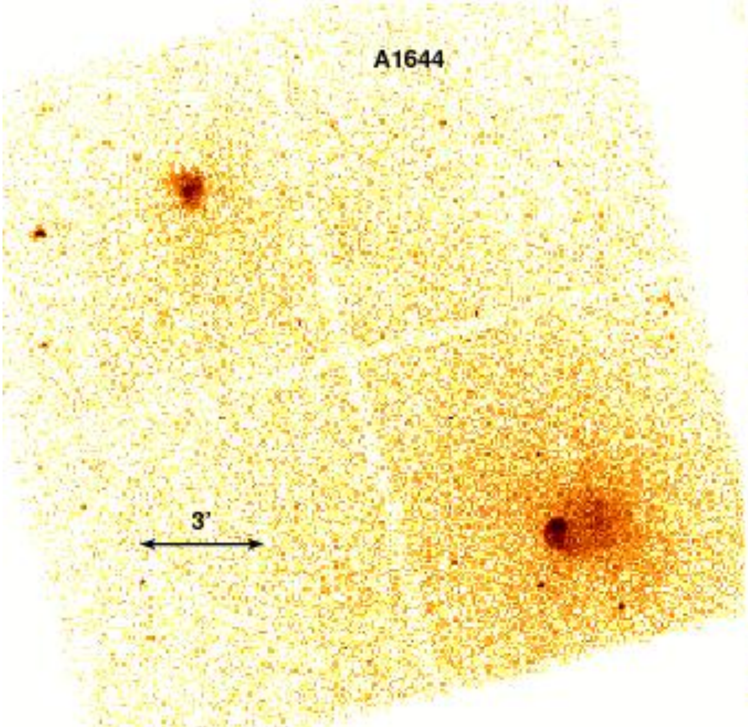
- Unique laboratory - see radiative losses, re-acceleration, mixing displayed spatially with time stamp from hydrodynamic flow
- IXO observations
  - abundances as tracer of gas motion
  - Map the gas velocity

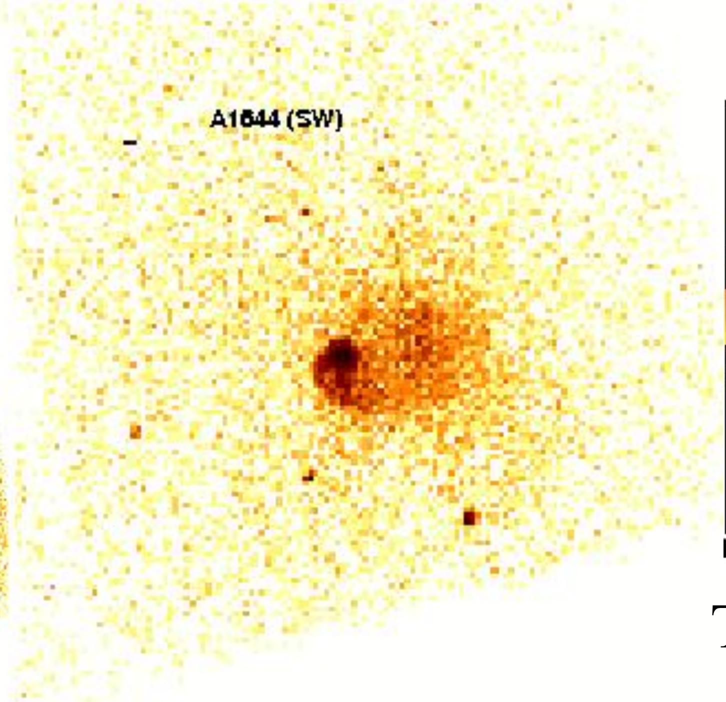


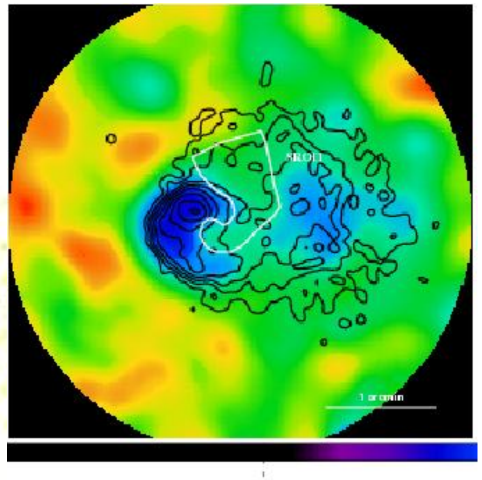


- lensing - map entire cluster
- full scale simulation
  - how long to establish circulation?
  - many merger cold fronts; how common is circulation
- **Puzzle of peculiar morphology - resolved!**
  - **fluid flows within cold fronts explain radio morphology**

Cluster Near Misses - more common than major mergers A1644 (Reiprich+2005, Johnson+2010)



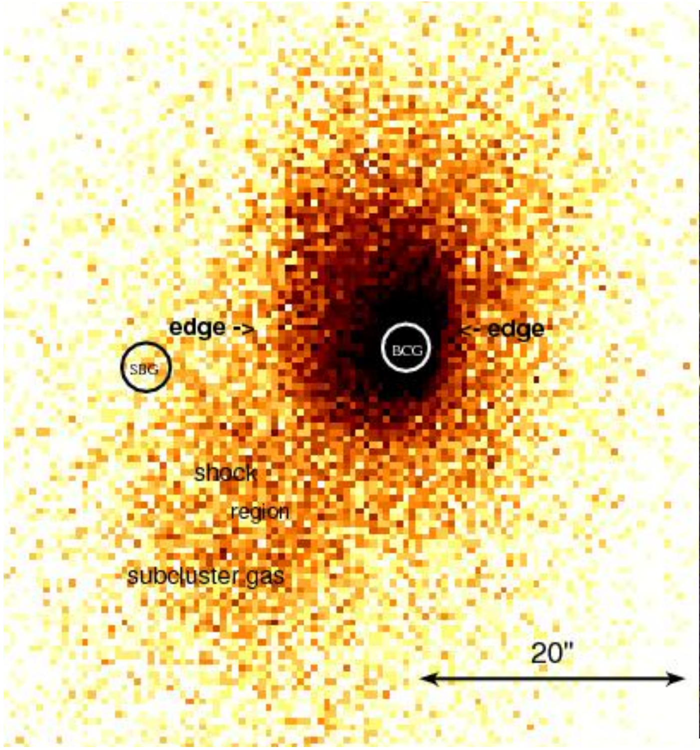




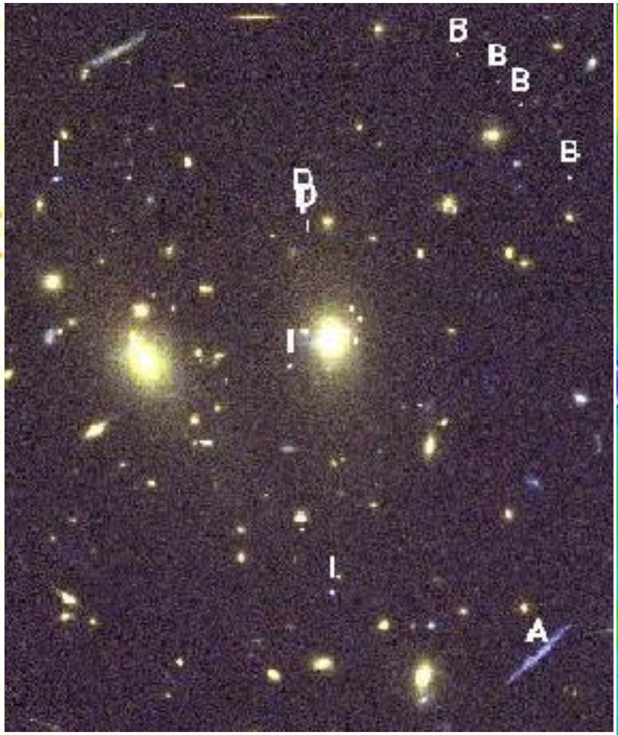
Temperature map

Spiral structure in surface brightness and temperature due to gas sloshing caused by the northern subcluster at least 700 Myr ago.

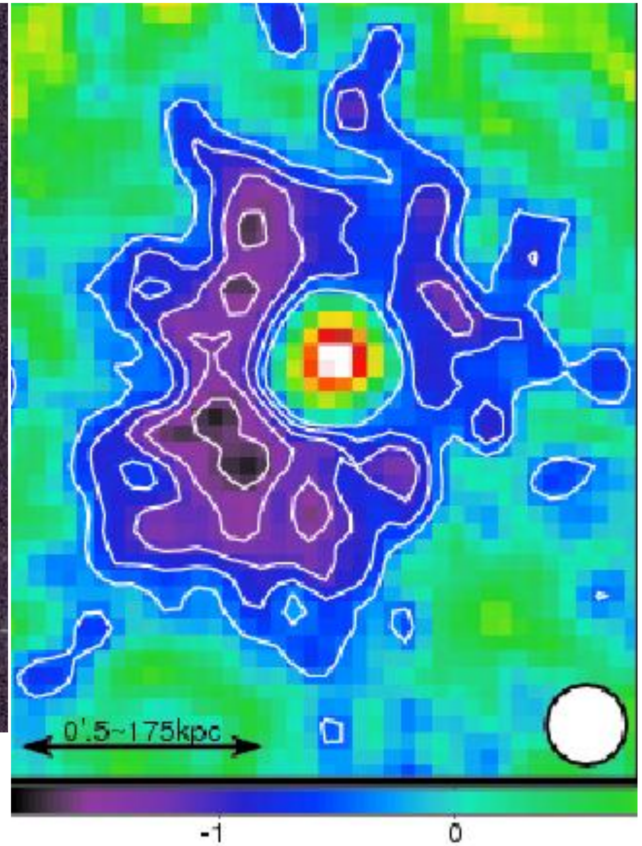
RXJ1347 (z=0.451) - gas sloshing in the most X-ray luminous known cluster



Chandra X-ray

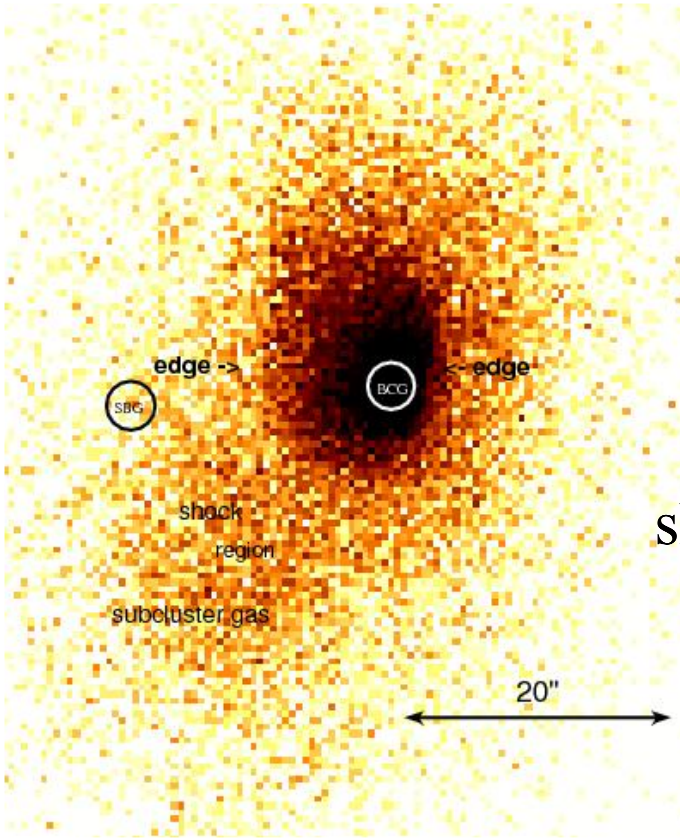


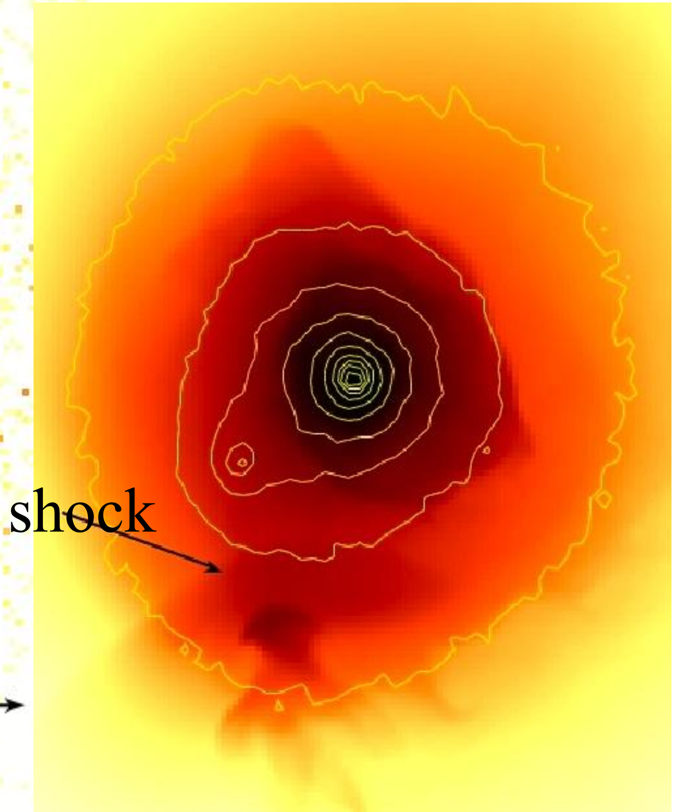
HST/ACS lensing
Bradac+ 2005



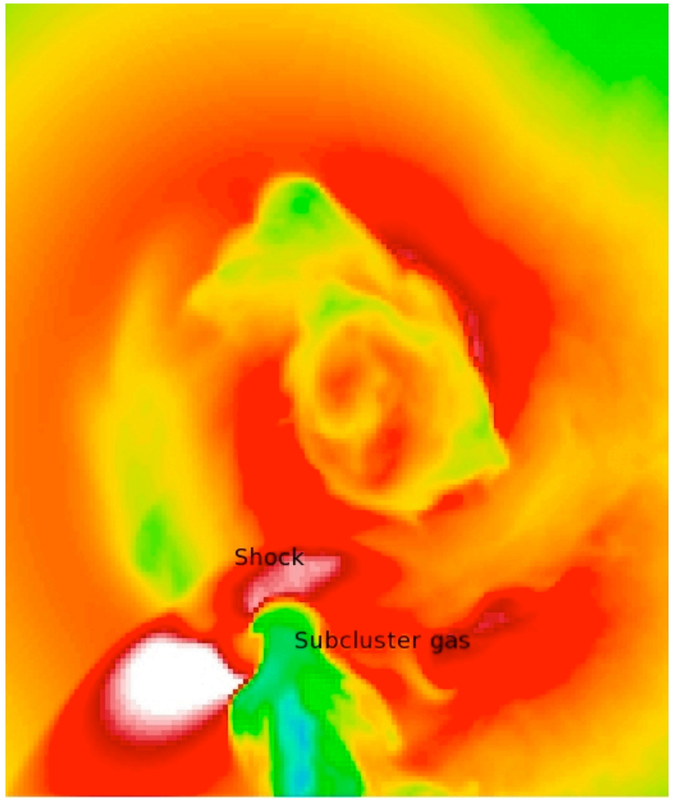
GBT/Mustang SZ
Mason+10

RXJ1347 - gas sloshing in the most X-ray luminous known cluster





DM contours on SB



Simulated temperature map (Zuhone)

In subcluster, gas has been stripped and “second” cD galaxy is ahead of gas

Future cluster physics “To do” list

Measure cluster growth and their thermodynamic evolution from $z \sim 2$

Understand ICM heating (by mergers and AGN) and evolution of gas entropy

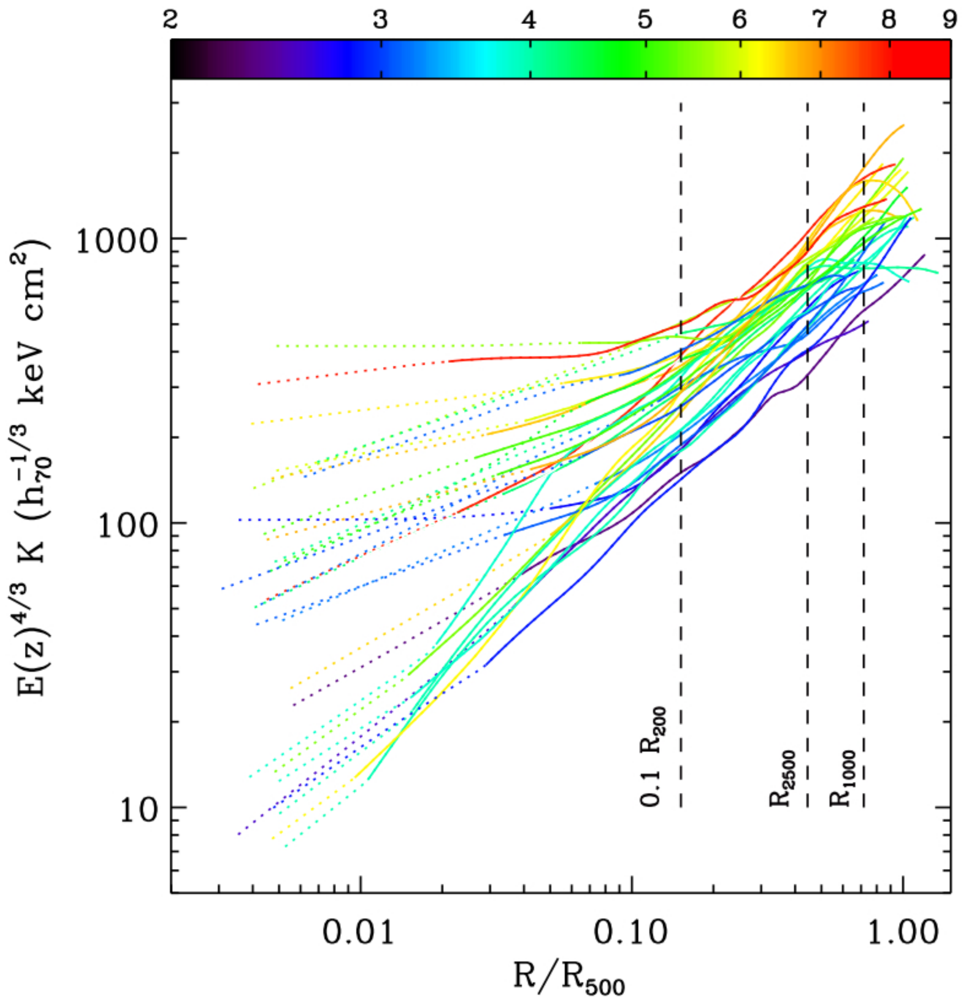
Understand ICM enrichment SN driven winds and galaxy stripping

Observe effects of mergers (&sloshing) on baryons and dark matter in large samples of systems from groups to rich clusters

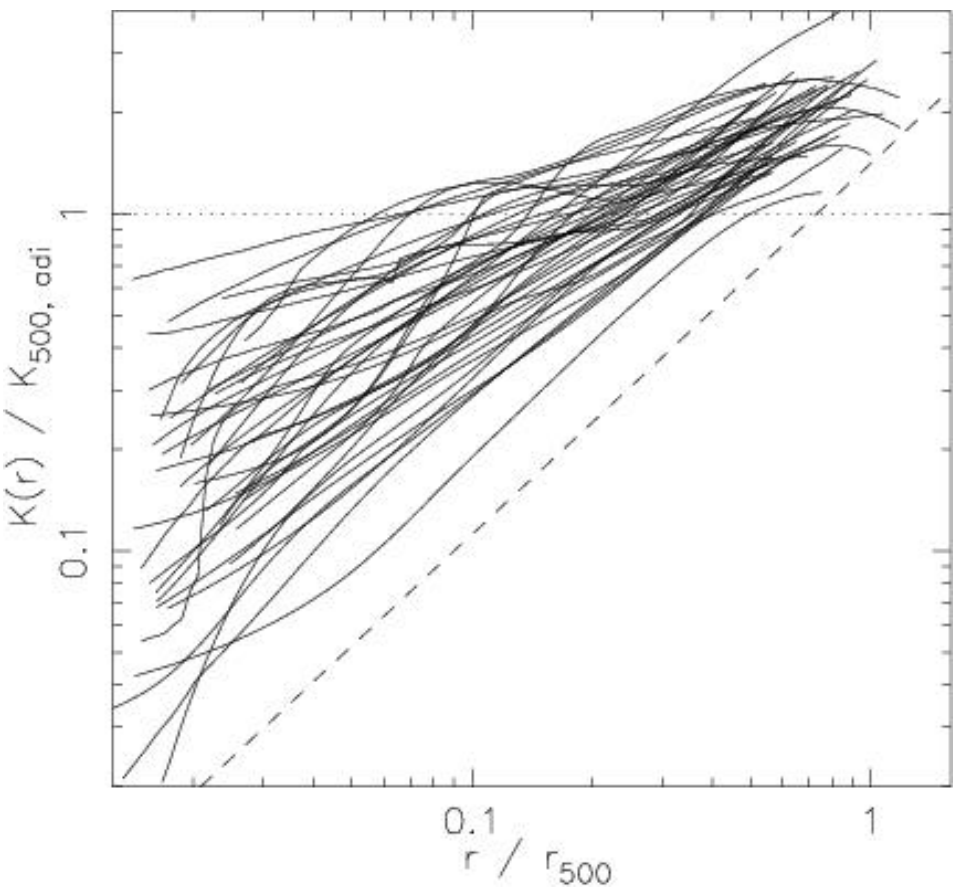
Understand origin of non-thermal emission - radio halos + X-ray hard component - and measure non-thermal pressure support

Need multiwavelength observations (e.g. lensing, radio maps) and simulations, in addition to X-ray

Entropy profiles for clusters and groups



Clusters (Pratt et al.)



Groups (Sun et al.)